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TECHNICAL REPORT NO. 6-691

INVESTIGATION OF EXPANDING CEMENTS

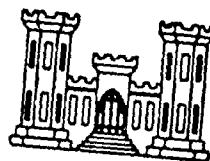
Report 1

SUMMARY OF INFORMATION AVAILABLE
AS OF 1 JULY 1963

by

Bryant Mather

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September 1965

Sponsored by

Office, Chief of Engineers
U. S. Army

Conducted by

U. S. Army Engineer Waterways Experiment Station
CORPS OF ENGINEERS
Vicksburg, Mississippi

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FOREWORD

This investigation was authorized by the Chief of Engineers by first indorsement, dated 14 May 1963, to a letter, dated 10 May 1963, subject: "Project Plan for Research on Properties of Cementitious Materials-- Investigation of Expanding Cements," and forms a part of item 614 of the Civil Works Engineering Studies program.

The work was done at the U. S. Army Engineer Waterways Experiment Station (WES) under the direction of Mr. Thomas B. Kennedy, Chief, Concrete Division, by Mr. Bryant Mather who prepared this report.

Col. Alex G. Sutton, Jr., CE, and Col. John R. Oswalt, Jr., CE, were directors of the WES during the investigation and the preparation and publication of this report. Mr. J. B. Tiffany was Technical Director.

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SUMMARY

It has been known for more than a century that the reaction of calcium aluminate with sulfate ion to form calcium sulfoaluminates (or "calcium aluminum sulfates") is accompanied by an increase in volume. During most of this period, the reaction has been regarded wholly as a harmful one, the consequences of which are deteriorative or destructive to concrete. This report attempts to review and summarize available information on expanding cements, as developed both in the United States and elsewhere, from the standpoint not only of the chemical and physical mechanisms involved, but also of the potential and actual applications that might be made of these products by the Corps of Engineers.

Beginning with the work of Lössier in the 1940's, continuing with work in the U.S.S.R. in the 1950's, and the work of Klein and associates in the United States in 1958, this reaction has been studied with a view to employing the resultant volume increase to achieve beneficial results.

The general consensus is that much basic knowledge needs to be obtained regarding the numerous potential expansive combinations of materials to relate their behavior to the specific physical-chemical mechanisms that are involved.

It also appears to be true that, in spite of major gaps in fundamental knowledge, certain specific formulations involving specific materials have been and are being used successfully in full-scale engineering applications. In the U.S.S.R. extensive development of a concrete pipe manufacturing plant designed to utilize expansive cement has taken place. The status of the U.S.S.R. work in 1961 was given in these words: "These results permit us to consider shotcrete casting as the chief method for manufacture of large diameter pressure pipes." It is therefore not clear from this review that the routine use of expansive cement in the industrial manufacture of concrete products has been achieved in the U.S.S.R.

In the United States, a variety of experimental projects has been completed or is under way. Some of these have involved model structures, others involve full-scale elements including pipes and pavements.

INVESTIGATION OF EXPANDING CEMENTS

SUMMARY OF INFORMATION AVAILABLE AS OF 1 JULY 1963

PART I: INTRODUCTION

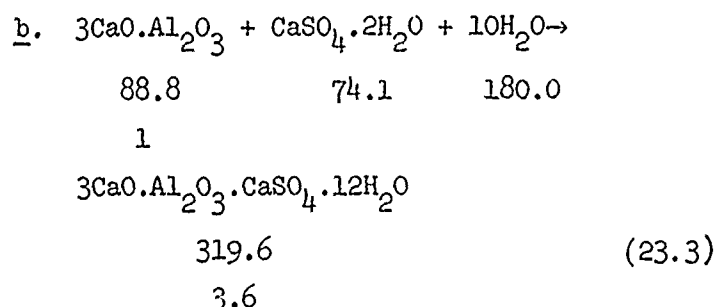
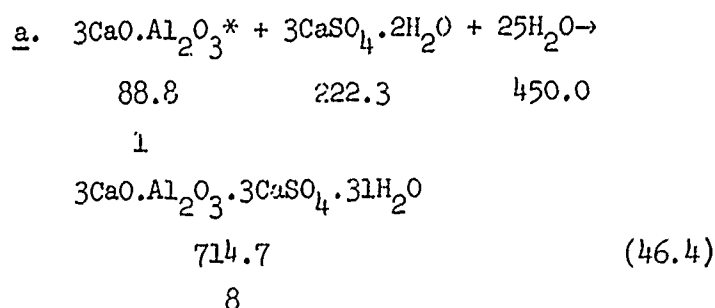
Background

1. Volumetric stability is a characteristic of portland cement concrete that has generally been sought but has never been completely attained. Slight volumetric instability will always have to be tolerated since it appears impracticable to develop a concrete that has no tendency to expand (or swell) on heating or on wetting, no tendency to contract (or shrink) on cooling or drying, and is completely free from any tendency to shrink on initial loss of moisture or from any tendency to expand or contract due to chemical reactions that occur during or after placement.

2. It has been suggested by Lorman^{1*} that the terms "shrinkage" and "swelling" as applied to concrete be limited to changes in volume due to changes in moisture condition, i.e. drying or wetting, and that the terms "expansion" and "contraction" be limited to changes in volume due to changes in temperature, i.e. heating or cooling. Powers² has noted that it is convenient to follow this usage and has proposed additionally that volume change produced by the freezing of water in concrete be designated "dilation," the reverse of which is "collapse." In this report the term "expansion" is also used for increases in volume caused by identifiable chemical reactions involving the production of reaction products that produce such an increase. This usage is analogous to that by which the term "autoclave expansion" is applied to the increase in volume due to hydration of calcium oxide or magnesium oxide, and that in which the term "expansion" is used for the length change of mortar bars in sulfate resistance tests. In the latter case the change in volume results from an aluminate-sulfate reaction to form sulfoaluminates in a manner similar in many respects to the mechanisms of expanding cements.

* Raised numerals refer to similarly numbered items in Selected Bibliography at end of text.

3. Hansen and Offutt³ state the reactions of tricalcium aliminate, gypsum, and water that produce the two forms of calcium sulfoaluminate as follows:



The numbers in the first line below the formulas are volumes participating in the reaction. The number in parentheses is the volume added to the volumes on the right side of the equation so that they equal the sum of the volumes on the left side. It is noted that the reaction products occupy less volume than the sum of the volumes of the reactants, i.e. both of these reactions take place with a contraction in volume. If the reactants dissolved and then precipitated as the reaction products, there should be a contraction. The second row of numbers is the ratio of the volume of the anhydrous tricalcium aluminate to the volume of the calcium sulfoaluminate product. In the first case the volume of the product is eight times the volume of the tricalcium aluminate used in its formation.

4. Efforts have been made to perfect techniques for selecting and using concrete materials so as to prevent excessive volume change. Certain specification requirements for portland cements and aggregate exist because it has been found that their imposition tends to prevent the use of materials that are responsible for either excessive shrinkage, or contraction,

* Subscript 3 was originally given as "4," a typographical error.

or excessive swelling, or expansion. Efforts have also been made to counteract the residual, apparently unavoidable tendency of compositions based on the use of portland cement as a binder to shrink on drying. These efforts have found their most successful applications in the production of preplaced aggregate concrete and so-called "shrinkage-resistant grouts." Both of these applications have been the subject of investigations at the U. S. Army Engineer Waterways Experiment Station (WES) as part of the Civil Works Engineering Studies program.^{4,5}

5. In recent years, especially with the extensive development of the technology and use of prestressed concrete, there has been a growing interest in and development of expanding cements. This has not been merely to tend to compensate for the inherent residual shrinkage due to drying or carbonation of concrete, but to develop positive stress, "self-stress," in restrained concrete members. The position of the Corps of Engineers regarding prestressed concrete was stated as follows:

Perhaps the most important application to date of prestressed concrete in Corps of Engineers civil works structures has been in anchorages for tainter gates. In addition to the advantages of reduced deflections between the no-load and loaded conditions and the resulting more favorable stress condition in the concrete piers, the use of prestressed anchorages has resulted in a significant economy over conventional anchorages. Prestressed concrete is also being utilized in the construction of bridges and powerhouse roof slabs.⁷

Purpose and Scope of This Report

6. This report attempts to review and summarize available information on expanding cements, as developed both in the United States and elsewhere, from the standpoint not only of the chemical and physical mechanisms involved, but also the potential and actual applications that might be made of these products in the civil works program of the Corps of Engineers.

Corps of Engineers Policy on Expanding Cements

7. In its report⁷ to the U. S. Senate, the Corps of Engineers made the following comments regarding expanding agents as concrete admixtures:

This is not a new class but new materials do occasionally become available. These materials perform the function of counteracting the shrinkage (setting shrinkage) which occurs during the early stages of stiffening. They find usefulness primarily in mortars and concrete for setting machinery bases and in certain special types of concrete such as preplaced aggregate concrete. Small quantities of aluminum powder are useful for this purpose and some of the products on the market sold for this purpose are basically aluminum powder. Others use other metallic forms including finely divided iron. The behavior of these materials particularly those including iron is difficult to predict and control. Composition of the portland cement used with these materials substantially affects their behavior and performance. The corps is currently engaged in an investigation aimed at developing improved purchase specifications and practices for use of these materials. When perfected these will eliminate the need to refer to these materials in contract specifications by trade name "or equal" and will provide for improved performance of these materials in corps work.

This is the only statement of the Corps of Engineers policy regarding expansive compositions that was located during this review.

PART II: STATUS OF KNOWLEDGE OF EXPANSIVE CEMENTS IN 1952 AND 1956

Status in 1952

8. Lafuma⁸ reviewed available data on expansive cements as of 1952 and summarized them as follows:

The disadvantages of the shrinkage of cement are well known and attempts have been made to counteract this shrinkage by bringing opposing factors into play. Prominence has been given to the advantages that could be derived from a slight expansion of the cement with regard to the characteristic properties of concrete.

The first satisfactory solution for industrial purposes was found by Hendrickx, activities in this sphere having been stimulated by Lossier to whom we owe the chief applications.

The necessity of obtaining a controllable expansion that will remain constant with time practically enforces the use of Candlot's salt as the expansion agent; it is made from a sulpho-aluminate clinker obtained by burning a mixture of gypsum, bauxite and carbonate of lime.

Expansive cement, properly so called, is prepared from a ternary mixture comprising:

Portland cement, which imparts its particular properties to the final product;
sulpho-aluminate clinker, which is the expansion agent;
blastfurnace slag, the stabilizing agent, the slow action of which enables the expansion to take place besides absorbing the excess of sulphate of lime.

The composition of the three constituents, their relative proportions, and their fineness are the principal factors whose influence should be considered with regard to obtaining the required expansion.

A more extended excerpt from his paper⁸ is given in Appendix A.

Status in 1956

9. Lea⁹ summarized knowledge of expanding and nonshrinking cements in 1956 as follows:

The value of a cement which would suffer no overall

change in volume on drying has long been realised, while for some purposes, such as underpinning and other types of repair work, a small overall expansion which would tighten the joint between new and old work would have advantages. It is to Lossier in France that the application of such cements is due, the methods of manufacture being developed by R. Perre at the firm of Poliet et Chausson. Essentially these cements^[8,10,11,12] consist of three elements (1) a Portland cement, (2) an expanding agent, (3) a stabiliser. As originally developed in France, the expansive agent was produced by burning a mix of 50 per cent. gypsum, 25 per cent. red bauxite and 25 per cent. chalk which it was thought might produce an anhydrous calcium sulphoaluminate clinker that would expand on reaction with water. Actually the product proved to be a mixture of some 38 per cent. calcium sulphate, 38 per cent. calcium aluminate, mainly $5\text{CaO} \cdot 3\text{Al}_2\text{O}_3$, and ferrites, and 20 per cent. γ $2\text{CaO} \cdot \text{SiO}_2$. The essential expansive agent was thus the mixture of calcium sulphate and calcium aluminate. A mixture of high alumina cement and calcium sulphate should, therefore, be an alternative but, since the rates of reaction of the constituents is an important factor, it has been found convenient to continue to use the clinker. The theory of the expansive action has not been clearly demonstrated, but it must be presumed to be made up of two parts, the reaction of the calcium sulphate and the tricalcium aluminate of the Portland cement and the reaction of the calcium sulphate and the less basic aluminate in the "sulphoaluminate" clinker. It is well known that a cement can be made from calcium sulphate and high alumina cement, or from calcium sulphate and blastfurnace slag, which has no expansive properties, but in the presence of a high lime concentration in solution arising from the Portland cement, depressing the solubility of the aluminates, the formation of the sulphoaluminate from these materials causes expansion. The function of the stabiliser, which is blastfurnace slag, is to slowly take up the excess calcium sulphate and bring the expansion to an end. By a judicious proportioning of the three elements it was possible to produce a cement in which the expansion just offset the drying shrinkage--the non-shrinking cement--or with a small overall expansion--the expanding cement. A minimum proportion of 8 per cent. of the "sulphoaluminate" clinker by weight of the Portland cement is required and the safe maximum is about 20 per cent. The slag content varies from about 15 per cent. upwards.

The expansion only continues as long as the concrete is kept moist and careful control of curing

is therefore necessary, particularly as it is apparently difficult to make successive batches of the cement with the same expansive characteristics. The non-shrinking cement is in a sense misnamed, since the neat cement expands about 0.2-0.4 per cent. during the first week of wet curing and then, when allowed to dry, shrinks by about the same amount. The expanding cement is adjusted so as to give an expansion of 1-2 per cent. for the neat cement over a period of wet curing of about 10 days as a maximum. In concrete the expansions are, of course, less than in neat cement and, according to Lossier, about 15 per cent. of that of the neat cement for a 1 : 2 : 4 concrete, about 20 per cent. for a 1 : 1-1/2 : 3 concrete, and about 50 per cent. for a 1 : 1 mortar. These ratios, however, vary with the aggregate and the cement and some tests only show much lower expansions. The strength of these non-shrinking and expanding cements is somewhat lower than that of Portland cement at ages up to 7 or 28 days.

The production of these cements has so far been only on a very small scale and they have been used only for special structural repair work under close supervision. In view of the necessity to terminate moist curing when the desired expansion has occurred, close supervision appears essential.

Other methods of producing expanding cements have also been examined. Mixtures of Portland cement, granulated slag and gypsum were found by Keil and Gille^[13] to continue to expand over long periods, but with the addition of 10 per cent. of high alumina cement the main period of expansion was limited to the first 14 days. Portland cement, supersulphated cement and high alumina cement are another mixture claimed to be suitable,^[14] and also Portland cement, calcium sulphate and dried and ground hydrated pozzolanic cement.^[15] Calcined dolomite and hard-burnt lime are other suggestions for expanding agents, but control of the time and volume of the expansion is obviously essential and with such agents probably difficult.

PART III: DEVELOPMENTS BETWEEN 1952 AND 1961

10. The two major developments involving expanding cements between 1952 and 1961 were (a) improvement in procedures for and knowledge of the phenomena involved in expansive cements, and (b) greatly increased interest in its use in prestressed concrete technology. Also during this period a group at the University of California, of which the most active member was Alexander Klein, undertook work in this area for the first time in the United States. These developments are well illustrated in the following extract of a paper by Lin and Klein.¹⁶

Summary of Earlier Investigations

11. Lin and Klein noted that the initial major developments in expansive concrete occurred in France about 20 years ago,¹⁰ principally by Lessier. The expansive cement consisted of a blend of portland cement, a blast-furnace slag "terminator," and a ground clinker having a composition that included dicalcium silicates, calcium aluminates, and hard-burned calcium sulfate. Very little use is now being made of this cement in France since it is difficult to control the expansion, and the magnitude of self-stressing was generally inadequate for prestressed concrete.

12. Expansive concrete for pressure pipes has been investigated intensively in the U.S.S.R. since 1953.¹⁷ The expansive cements used in the U.S.S.R. are mixtures of portland cement, calcium-aluminate cement, and calcium sulfate (either gypsum or plaster). In the use of the French expanding concretes, mixing and placing of concrete was by conventional methods for concrete, but special methods of curing were required, both the slag terminator and cessation of water curing being used to end the expansion. In the U.S.S.R. the expansive mixture for pressure pipes is a mortar, having about 10 sacks of cementing material per cubic yard and being placed by shotcrete methods, centrifugation, or vibrosqueezing equipment. Final setting occurs in a matter of minutes, after which elements are coated with paraffin and kept in water at 20 C until the strength is considered adequate. Thereafter, the structural elements are placed in a water bath at 70 to 80 C, the paraffin melts off, and

the expansion of the mortar takes place under the action of the hydro-thermal curing. The curing is continued until the expansive reaction is completed, the degree of self-stress obtained being governed by the amount of restraint provided by the tensioned steel. Final curing is carried on under water at 20 C.

13. The earliest major research in the field of expansive concrete conducted in the United States was reported by Klein and Troxell¹⁸ at the University of California. This study was directed toward the use of calcium aluminosulfate clinkers and blast-furnace slag as admixtures to concretes to produce expansion. The principal contribution of their study was proof of the existence of a stable compound in the system $\text{CaO-Al}_2\text{O}_3\text{-SO}_3$, determination of its characteristic X-ray diffraction pattern, and those of the several hydrates of the particular calcium aluminosulfate anhydrite. The unrestrained expansions for mortars containing about 10 sacks of cementing material per cubic yard of mortar, were at best about 1.0 percent. With restraint, such expansions would be far too low to provide adequate stressing of steel and concrete for prestressing purposes.

14. Further studies of expansive concretes containing expansive cement of modified composition and properties, conducted at the University of California from 1958 to 1961, were reported by Klein, Karby, and Polivka.¹⁹ These studies covered tests of 2- by 2- by 1-in. concrete prisms and concrete pipes 12 in. long of 12-in. diameter and 2-in. wall thickness. They were made with expansive concrete chemically stressed through the mechanism of external restraint which was accomplished by steel rods or steel shells. The quality of the concretes was determined necessarily only after removal of the restraint.

15. The relations developed between strength and free expansion, strength and restrained expansion, strength and water-cementing material ratios for the expansive cements of various proportions provided the necessary significant information required for the design of concrete elements to be chemically prestressed employing internal restraint, and further, provided data for predicting and controlling the magnitude of expansion for the designed restraint.

Investigations by Lin and Klein¹⁶

16. The investigation described by Lin and Klein was a laboratory study which used internal restraint in specimens of pressure pipe and flat slabs approaching sizes used in practice. Pilot specimens were made and tested to correlate the chemical and physical properties of the cement and concrete with the behavior and strength of the various structural elements. The elements were provided with gages to enable measurement of strains developed in the steel and in the concrete as a result of the chemical prestressing process. After prestressing, the elements were cured and dried to conditions of practical equilibrium in order to provide data with respect to effects of anchorage or absence of anchorage on slip, and to stress losses incidental to slip, drying shrinkage, and creep. Finally, the elements were tested to determine the behavior and strength of the prestressed elements.

17. From the results, Lin and Klein concluded that the strength and the behavior of structural elements of the types fabricated and tested can approximately be predicted by conventional theory of elasticity and principles of prestressing, provided the chemical and physical properties of the concrete to be employed are determined in advance of design. At the same time, it became apparent also that certain factors, not considered highly significant in conventional concrete, may have a greater influence and will need further adequate study to permit accurate and reliable analyses and designs.

18. The immediate most promising application in the prestressing field lies in the production of pressure pipes, in which great savings in manufacture are clearly indicated. Also, in the field of airport and highway pavements, there is promise of practically crack-free jointless pavements made with concrete of relatively thin section to carry the required loads even under adverse subgrade conditions. The manufacture of precast thin shells and precast walls using expansive concrete also holds great promise, although the art and technique are yet to be developed. However, since eccentric prestressing with expansive concrete has not yet been investigated, there is no present indication of the economy or desirability of making either beams or floor panels.

19. In order to reduce variables to a practical minimum, only one composition of portland cement and one composition of expansive component were employed in the production of expansive cement and concrete in the investigation reported by Lin and Klein.

Prestressed pipes

20. Construction. Four pressure pipes, each 36 in. long, were manufactured and tested in the course of the investigation. For all pipes, the concrete contained 10 sacks of expansive cement per cu yd of concrete, the cement being a blend of 7 parts of type I portland cement (53 percent C3S, 4 percent C3A, low alkali) and 3 parts of preground calcium aluminosulfate clinker. A local sand (FM 2.67) and a No. 4 to 1/2-in. local gravel were used throughout for pipe concrete, the sand being 46 percent of the total aggregate. The ratio of water to expansive cement was 0.325 for pipe I and 0.31 for pipes II, III, and IV. A water-reducing retarder was used in the amount of 4 oz per sack of blended expansive cement. For all concretes used in this investigation, the mixing, placement, curing, and drying were conducted at approximately 70 F.

21. Although the concretes, mixed in a pan-type mixer, were quite stiff (slump 1/2 in.), they were satisfactorily placed through the use of a vibrating table designed for the purpose. Both internal and external casting forms for the pipes were of cardboard, 1/2 in. thick, treated with paraffin. The cardboard forms were removed at an age of 6 hr for pipe I, and at 24 hr for pipes II, III, and IV. Subsequent to casting, all pipes were stored in fog at 70 F, 30 days for pipes I and II, 20 days for pipe III, and 50 days for pipe IV. After fog-curing was completed, the pipes were stored under drying conditions at 70 F and 50 percent relative humidity.

22. In order that self-stress values in steel and in concrete could be determined, SR-4 gages were fixed to the steel reinforcement and were waterproofed, and specially constructed waterproof gages were embedded in the concrete. Smooth rods were also employed in addition to strands for longitudinal reinforcement to facilitate mounting strain gages. Gage points were provided on the surfaces of the pipes for observation of length changes by means of Whittemore gages. Wire strain gages were provided to allow measurement of stresses in both circumferential and

longitudinal steel reinforcement. For pipe II, gages also were placed along the longitudinal strands to study the development of bond.

23. As determined previously,¹⁹ this concrete in the absence of restraint may have undesirably high free expansion and low strength. However, when adequate restraint is provided against expansion, even in one direction, concrete of high compressive strength can be produced. To obtain optimum economic stress in the high-tensile steel, an expansion of the order of 0.6 percent would be required. Assuming an elastic modulus E_s of 28,000,000 psi, this magnitude of strain would produce an initial prestress in the steel,

$$0.006 \times 28,000,000 = 168,000 \text{ psi.}$$

To insure bond between steel and concrete before the development of prestress, the concrete must gain strength at a rapid rate to a value sufficient to establish adequate bond before the expansion becomes of too high a magnitude. Furthermore, the expansion must substantially terminate at a predetermined age and maintain a stabilized level with subsequent curing. It is desirable also that subsequent drying shrinkage and creep of the concrete be of limited amount. It is apparent that the percentage of steel reinforcement must correctly be chosen to obtain the predetermined strain in the steel. Such design involves a predetermined relation of the expansion of the given concrete and the percentage of internal steel reinforcement or restraint for given anchorage conditions. At high values of steel stress, where slip may occur, adequate anchorage also is involved in the design.

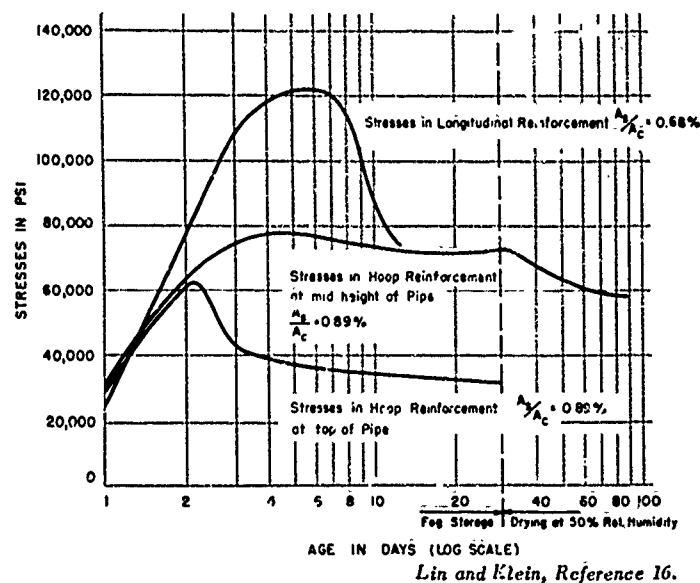
24. For the four pipes the development of stresses in the circumferential and longitudinal steel and in the concrete are shown in subsequent figures, and a summary of the significant values of pipe dimensions and of stress development is given in table 1 (page 19).

25. It is noted that the maximum stresses developed in the steel were about 100,000 psi, which was sufficient for test purposes. The magnitudes of the steel stresses can be significantly increased by (1) decrease in the amount of steel reinforcement--the most economical procedure; (2) increased expansion of the concrete--in the present instance the least

economical; and (3) both decrease in the amount of steel and improved anchorage to reduce stress loss due to slip.

26. Fig. 1 indicates the development of self-stressing in pipe I

Fig. 1. Tensile stresses in reinforcement of pipe I due to expansive self-stressing

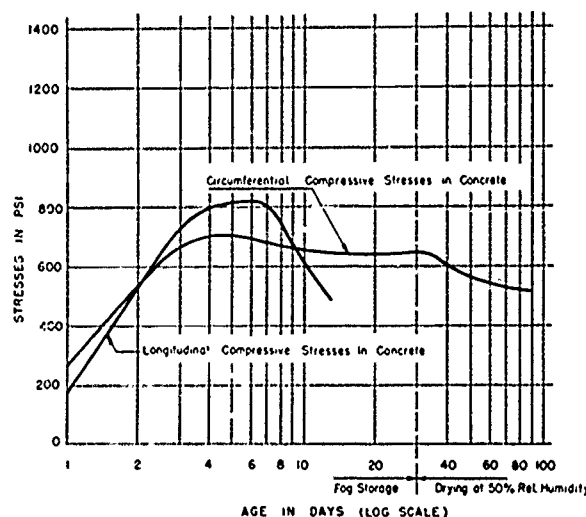


during 30 days of curing in fog at 70 F, and of subsequent drying at 70 F and 50 percent relative humidity to 90 days age. Stresses greater than 120,000 psi were developed in the longitudinal strands, although no mechanical anchorage was provided.

27. The corresponding compressive stress in the concrete in the longitudinal direction was 800 psi. It is apparent that good bond existed between the strands and the concrete as early as 4 days age. However, the rapid increase in tensile and bond stresses on longitudinal steel resulted, in the absence of appropriate anchorage, in a bond failure and subsequent slip at 6 days age. This slip resulted in a notable reduction of stress in the longitudinal reinforcement, amounting to about 35 percent. Due to the slip, the gages were damaged and no reliable observations were possible after 12 days age.

28. The tensile stresses developed in the hoop reinforcement at midheight of the pipe were almost stable at 5 days age, resulting in a compressive stress of about 650 psi in the concrete. A reduction of stress was observed in the hoop reinforcement at the top of the pipe, again probably due to slip and lack of anchorage.

29. The corresponding maximum compressive stresses in the concrete



Lin and Klein, Reference 16.

Fig. 2. Compressive stresses in concrete of pipe I due to expansive self-stressing

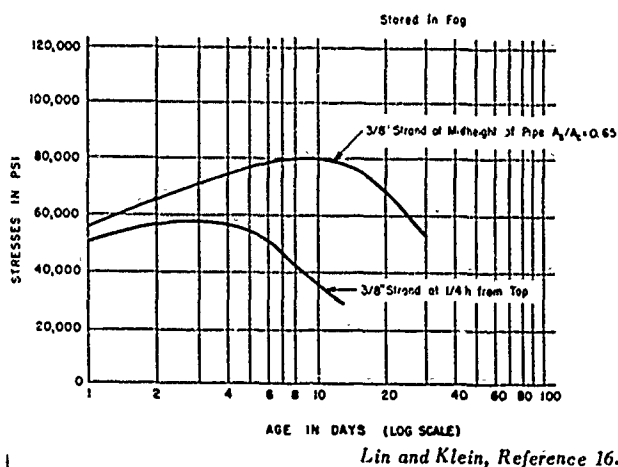
are shown in fig. 2. These stresses were calculated under the assumption that the entire cross section of the pipe was uniformly stressed. When the pipe was exposed to drying, a reduction of stress in the concrete occurred in the amount of about 120 psi. The final effective self-stress was thus found to be 530 psi.

30. The observed behavior of the pipe while curing in fog is of interest. Circumferential cracking, or delamination, in the top end of the concrete pipe was observed for both pipes I and II, and substantial increased expansion at the top strip, both due to lack of adequate restraint. It is noteworthy that no delamination or unrestrained expansion occurred at the bottom of either pipe I or pipe II, restrained only by bearing the weight of the pipes.

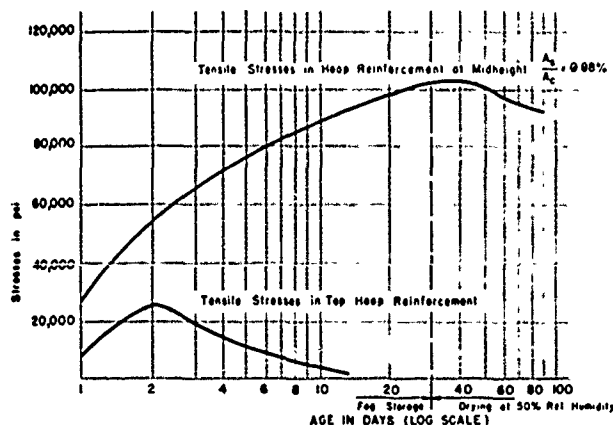
31. From tests conducted on externally restrained bars of concrete, it appears that, if expansion is restrained in one direction (longitudinal in the case of the bars) sound concrete is produced. It appears also that in pressure pipe, if adequate bond stresses are developed, the pipe will be restrained longitudinally as well as circumferentially. The question still remains of the distance from the end of the longitudinal strands to the point where adequate bond stresses will be developed and how this distance is related to restraint of the top or end strip of pipe.

32. For pipe II the development of self-stressing of steel and of concrete is shown in figs. 3 and 4. As in the case of pipe I, stresses were determined from strain measurements, and again attention was given to the development of bond stresses along the longitudinal reinforcement. The stresses developed in the 3/8-in. longitudinal strand are shown in fig. 3 for positions at both the midheight of the pipe and the quarter-point below the top of the pipe, referred to the casting position. As in the case of

Fig. 3. Tensile stresses in longitudinal reinforcement of pipe II due to expansive self-stressing



Lin and Klein, Reference 16.

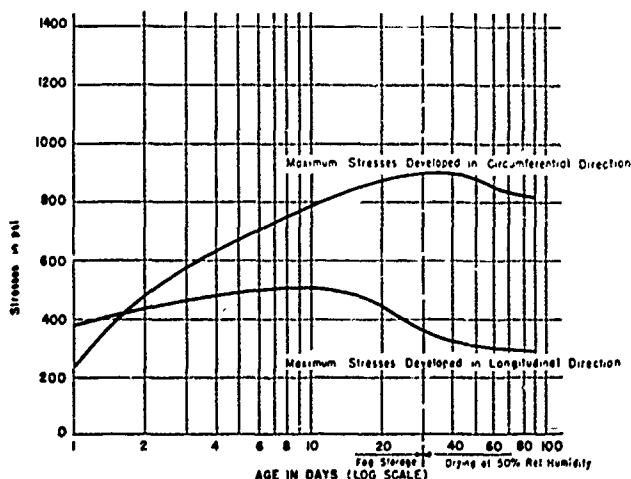


Lin and Klein, Reference 16.

Fig. 4. Tensile stresses in hoop reinforcement of pipe II due to expansive self-stressing

pipe I, anchorage was provided by bond only. Tensile stresses amounting to 58,000 psi and 80,000 psi were developed in the longitudinal reinforcement at quarter-height from the top and at midheight of the pipe, respectively. The corresponding maximum compressive stress developed in the concrete in the longitudinal direction (fig. 5) was 500 psi. Also as in the case of pipe I, bond failure, slip, and consequent stress reduction occurred, first at quarter-height from the top, and subsequently at mid-height of the pipe.

33. In fig. 4, development of self-stress in the hoop



Lin and Klein, Reference 16.

Fig. 5. Compressive stresses in concrete of pipe II due to expansive self-stressing

reinforcement of 1/4-in.-diameter smooth wire is indicated both at the top of the pipe as cast and at midheight of the pipe. Although the hoop reinforcement for pipe II using 1/4-in. smooth wire was heavier than the 1/8-in. smooth wire used in pipe I, the percentage of circumferential steel was kept the same in both pipes by increase of pitch in pipe II to 3 in. as compared to a pitch of 1 in. for pipe I.

34. By 14 days age, tensile stress over 90,000 psi was developed at the midheight of the pipe; at 30 days age, tensile stress was over 100,000 psi. However, stress in the hoop reinforcement at the top of the pipe was negligible due to lack of bond or of adequate anchorage.

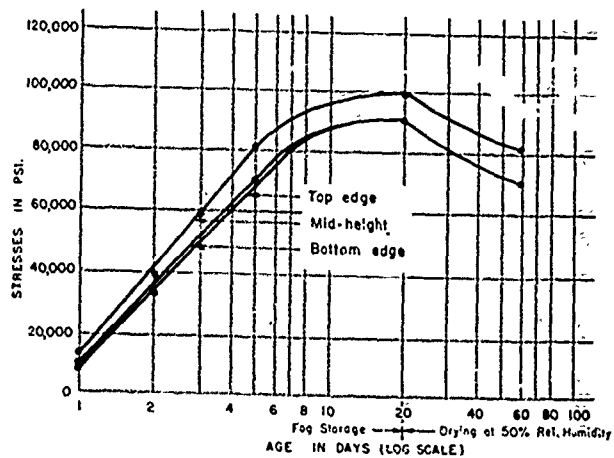
35. The respective maximum compressive stress developed in the concrete (fig. 5) was about 920 psi in the circumferential direction. When the concrete was exposed to drying at 70 F and 50 percent relative humidity, a stress reduction of about 110 psi occurred, the final effective prestress amounting to 810 psi in the circumferential direction (and about 280 psi in the longitudinal direction).

→ 36. Although the performance of the pipe appeared to be satisfactory, again cracks were observed at the top of the pipe around the hoop reinforcement. The laminar cracks appeared only on the upper surface at the top end of the pipe. These cracks proved that the top strip was not adequately restrained and consequently expanded freely outside the restraining hoop reinforcement. Other parts of the pipe were stressed satisfactorily because of the restraint resulting from development of bond along the longitudinal strands.

37. A study of the behavior of pipes I and II suggested a design to overcome the localized cracking and to produce an adequately self-stressed pipe for subsequent tests under hydrostatic pressure.

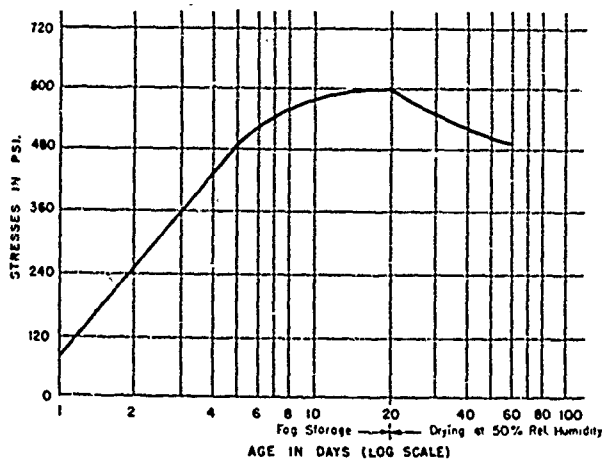
38. Pipe III differed from pipes I and II in that special anchorage was provided for each of the 1/4-in.-diameter longitudinal high-tension wires, utilizing washers and wedges. In addition, expanded-metal rings were placed at both top and bottom ends of the pipe to eliminate unrestrained sections of the concrete pipe. Special care also was taken to provide adequate anchorage for the hoop reinforcement. The development of circumferential stresses in pipe III is illustrated in figs. 6 and 7. The major amount of the prestress was developed in less

than 7 days. When the pipe was subjected to drying at 70 F and 50 percent relative humidity, drying shrinkage and creep accounted for a stress loss of about 20,000 psi or about 20 percent. It is of particular interest that with the special anchorage on the hoop reinforcement, stresses in the hoop reinforcement were identical at both top and bottom edges of the pipe at about 92,000 psi, and but slightly greater at the midheight



Lin and Klein, Reference 16.

Fig. 6. Tensile stresses in hoop reinforcement of pipe III due to expansive self-stressing



Lin and Klein, Reference 16.

Fig. 7. Circumferential compressive stresses in concrete of pipe III due to expansive self-stressing

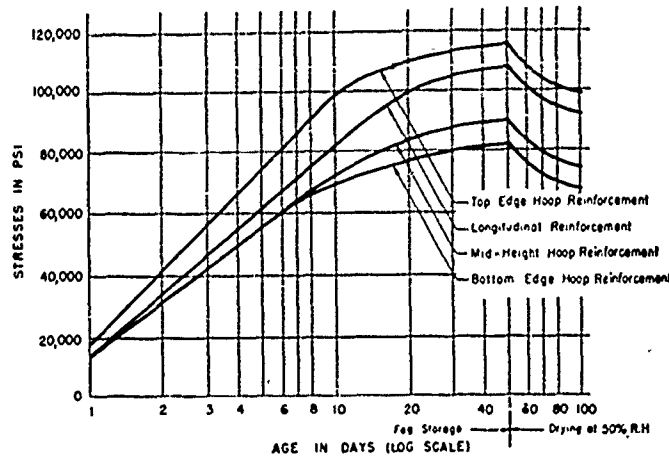
with respect to the satisfactory resistance of the pipe to internal pressure and to center loading resistance. However, most important, pipe III proved that the objectionable slip phenomena can readily be overcome with adequate anchorage.

39. The design of pipe IV was practically identical with that of pipe III, except that the expanded-metal rings used in pipe III to prevent cracking at the top concrete layer were omitted in the fabrication

of the pipe at 100,000 psi. Although the percentages of steel in both longitudinal and hoop reinforcement were substantially less than for pipes I and II, steel stresses were about equal to the stresses obtained in pipes I and II. While the stress in the concrete was only 600 psi, as compared to 700 psi for pipe I and 900 psi for pipe II (circumferential stresses at center of pipe), subsequent tests indicated that the economy of steel was justified

of pipe IV. The longitudinal steel was anchored with washers and wedges, and the anchors were subsequently embedded in the concrete during casting.

40. Figs. 8 and 9 show that stress development was almost linear at



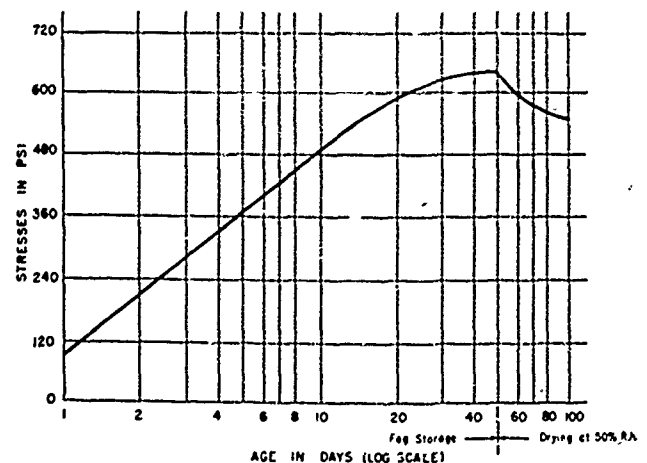
Lin and Klein, Reference 16.

Fig. 8. Tensile stresses in reinforcement of pipe IV due to expansive self stressing

the top edge and the midheight of the pipe, as compared to conditions in the hoop reinforcement at the bottom edge of the pipe. It is apparent that with horizontal casting of pipe instead of the vertical casting employed for the four pipes, and appropriate end restraints designed to accommodate shaped ends of pipe for joints, it should be possible to achieve relatively uniform stressing of hoop reinforcement throughout the length of the pipe.

41. While the maximum circumferential stress in the concrete at the center of the pipe, at 640 psi, was about the same as for pipe III, a longitudinal stress of 500 psi was obtained at the center of the pipe, as compared to only 370 psi for pipe III. Lin and Klein believed that the

all positions in the pipe up to about 9 days age, at which time about 80 percent of the maximum stabilized stresses was achieved. Neither bond failure nor slip occurred at any position in the pipe. However, the omission of the restraining rings of expanded metal resulted in somewhat higher expansion and somewhat higher stress in the hoop reinforcement at both



Lin and Klein, Reference 16.

Fig. 9. Circumferential stresses in concrete of pipe IV due to expansive self-stressing

relatively low longitudinal stress of 370 psi for pipe III was due to the use of six extra No. 3 anchored rods, added for the purpose of achieving greater rigidity of the steel "cage" against distortions or movement during casting. In the absence of the extra steel for rigidity in pipe IV, some displacement occurred in the hoop reinforcement due to heavy vibration during concrete placement. As a result of such displacement, the ratio of steel to concrete area at the top of the pipe was estimated to be about 0.5 percent while that at midheight and bottom was about 0.7 percent as compared to a design value of 0.60 percent throughout. In spite of the lack of end restraint at the top, and displacement of hoop reinforcement, the concrete stresses, developed along the pipe in the longitudinal as well as circumferential directions, were in close agreement. When pipe IV was exposed to drying conditions at 70 F and 50 percent relative humidity, stress loss due to drying shrinkage and creep amounted to about 19,000 psi in the steel and to 110 psi in the concrete, or an average stress loss of about 17 percent.

42. For rapid comparison, the dimensions, circumferential and longitudinal steel reinforcement, and maximum stresses developed in both steel and concrete at the center and ends of the pipes are summarized for all four pipes in table 1.

Table 1
Pipe Dimensions and Stress Developments

	Pipe			
	I	II	III	IV
<u>Dimensions</u>				
ID, in.	12	12	14	14
OD, in.	14.8	16	18	18
Wall thickness, in.	1.4	2	2	2
Pipe length, in.	36	36	36	36
<u>Circumferential steel</u>				
% of concrete area	0.89	0.88	0.60	0.60
Size and type	1/8-in. wire	1/4-in. wire	0.196-in. wire	0.196-in. wire
Pitch (spacing), in.	1	3	2-1/2	2-1/2
Outside concrete protection	1/2 in. clear	1/2 in. clear	1/2 in. clear	1/2 in. clear
<u>Longitudinal steel</u>				
% of concrete area	0.69	0.65	0.55	0.55
Size of wire, in.	1/4	3/8	1/4	1/4
Type of wire	7-wire strands	7-wire strands	Smooth high tension wire	Smooth high tension wire
Total No.	12	6	12	12
Anchorage	None	None	(+6 No. 3 rods) anchored	Anchored
<u>Max circumferential stress in steel, psi</u>				
Center	78,000	104,000	100,000	90,000
End	62,000	26,000	91,000	115,000
<u>Max longitudinal stress in steel, psi</u>				
Center	122,000	80,000	66,000	108,000
End	--	57,000	66,000	--
<u>Max stress in concrete, psi</u>				
Circumferential, center	700	900	600	610
Longitudinal, center	820	500	370	500

43. Tests of pressure pipes. The tests of the pipes by external loading included subjecting the pipes to internal hydrostatic pressures to failure, and subsequently to center-load tests to failure.

44. For tests of resistance to internal pressure, the pipe to be tested was first sealed at both ends by means of O-rings and steel plates. Then the pipe was filled with water through an inlet in the steel plate at the bottom of the pipe, and pressure was applied first to zero compression in the concrete and then to the cracking load. After being unloaded the pipe was reloaded to recurrence of leakage. Only pipes I, III, and IV were tested in this manner.

45. All four pipes were subjected to the center-load test, also known as the three-edge bearing test. In testing pipes I, III, and IV by the center-load test subsequent to completion of testing by internal pressure, the pipes were set horizontally on the bearing block in such manner that the position of the crack from the internal-pressure test made an angle of 45 deg with the vertical.

46. The results of all loading tests on the four pipes are summarized in table 2. Based on these results, it is apparent that for the particular composition of expansive concrete employed in their manufacture, a maximum prestress in the embedded steel between 80,000 and 120,000 psi can be obtained as a result of the chemical prestressing. Because of creep and drying shrinkage, stress losses occur amounting to a maximum of about 20,000 psi. Some anchorage is necessary for both longitudinal and circumferential steel in order to insure bond between steel and concrete.

Table 2
Results of Pipe Tests

	Pipe			
	I	II	III	IV
<u>Internal Pressure Tests</u>				
Average effective circumferential prestress, psi	530	810	490	530
Observed internal pressure at leakage, psi	360	--	220	250
Theoretical internal pressure at leakage, psi (corresponding to assumed tensile strength of 0.10f _c)	300	--	270	310
Ratio of observed/theoretical values	1.2	--	0.82	0.82
<u>Center-Load Tests</u>				
Center load at observed cracking, lb	13,000	31,700	24,600	30,000
Center load at ultimate, lb	24,000	55,200	59,500	65,000
Theoretical ultimate load	23,800	48,500	53,600	63,500
Ratio of experimental/theoretical values	1	1.14	1.12	1.02

47. Table 2 shows that the ratio of experimental values to theoretical values is equal to 1 or more for the center-load tests, and is 1.2 and 0.8 for tests of resistance to internal pressure. Considering that these tests were preliminary and exploratory, and that no knowledge exists as to the state of stress in the chemically prestressed concrete, nor as to the relation between the state of stress, if known, and resistance to internal pressure, the authors believed that the correlation between experimental results and the approximations of theoretical values is surprisingly close.

Slabs

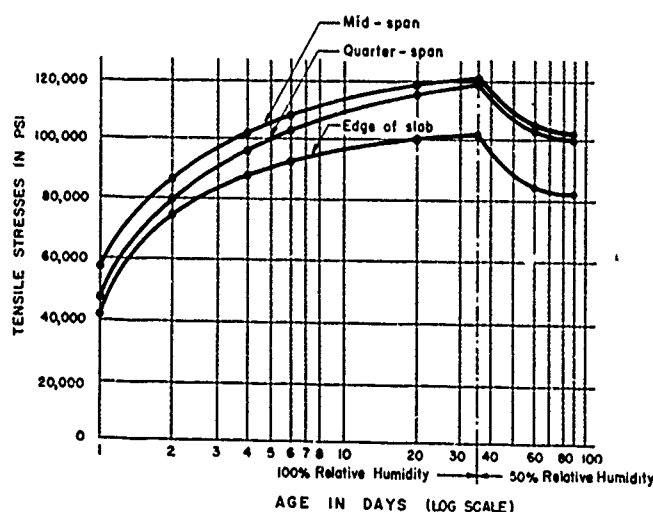
48. Following the investigation of chemically prestressed pressure pipes, a further exploratory study was carried on in the manufacture and testing of relatively thin slabs. Two slabs were manufactured in this series, one a 6- by 6-ft slab, 2 in. thick, with "two-way" reinforcement; the other a 5- by 8-ft slab, 3 in. thick, with "one-way" reinforcement. The concrete used in both slabs was of the same composition as that employed in the pressure pipes, except that the expansive-cement content was a total of 9 sacks per cu yd, of which 7 sacks was the portland cement and 2 sacks the expansive component. For the concrete used in the slabs the maximum size of aggregate was 3/4 in.

49. Two-way slab. The actual dimensions of the two-way slab were 6 ft 6 in. by 6 ft 6 in. by 2 in. at the time of casting. The reinforcement consisted of 1/4-in.-diameter, high-tension steel strands 6 ft 4 in. long. The spacing of reinforcement in each direction was 3 in. The wires in the first direction were all placed at the center of depth of slab, and the wires in the perpendicular direction were alternately placed first above, then below the steel of the first direction in order to insure symmetry of reinforcement. All reinforcement was fitted with a washer and a wedge at each end of each wire to provide anchorage against bond failure and slip. All steel was supported by wire chairs to prevent displacement during casting. The ratio of steel to concrete area was 0.59 percent in each direction.

50. Concrete, with water-cementing material ratio of 0.30, was mixed in a pan-type mixer; it contained 4 oz of a water-reducing retarder per sack of cementing material. The concrete, of 1/2-in. slump, was

placed with external vibration provided by a steel table. The form for the slab was placed on the steel table prior to casting, and the finished slab was initially cured in place on the steel table for two days, under burlap kept wet by continuously flowing water. At 2 days age, the slab was stripped, mounted vertically in a carrier, and transported for further curing to a fog room. Curing in fog at 70 F was continued to 35 days age. The slab was thereafter exposed to drying at 70 F and 50 percent relative humidity to 90 days age.

51. The development of stress in the steel reinforcement during curing and expansion, and subsequent stress loss on drying are shown in fig. 10. Expansion and stress development were determined at three positions in the slab--midspan,



Lin and Klein, Reference 16.

Fig. 10. Tensile stresses in reinforcement of two-way concrete slab due to expansive self-stressing

positions in the slab--midspan, quarter span, and near the edge. Stress development was found to be equal in rate and magnitude in both directions, the stress symmetry being subsequently verified by the crack pattern when the slab was tested to failure.

52. About two-thirds of the maximum stabilized stresses were developed within the first two days of water-curing. Thereafter, the rate of expansion and stress de-

velopment was somewhat slower than would have been the case with continued water curing instead of the fog-curing. The maximum steel stress produced at midspan was 121,000 psi, and the final value was 102,000 psi after stress loss due to drying shrinkage and creep. The final stress in steel at the quarter span was 100,000 psi, practically the same as at midspan. The final steel stress near the edge of the slab was about 82,000 psi. The reduced stresses near the edges of the slab are believed to be due to some slight movement of the anchor wedges at ends of steel strands, inasmuch as the concrete embedment gages at all three positions showed a

uniform maximum expansion of 0.40 percent.

53. It is indicated in fig. 11 that the average compressive stress in the concrete at the time of test (90 days) was about 560 psi. This value was utilized in calculating the theoretical bending moment and the theoretical ultimate stress, using the crackline theory.

54. The method of testing the slab was to hold down the four corners and apply a uniform load over the entire slab by applying air pressure to a rubber bag mounted underneath the slab. The clear span length was 5 ft 10 in. in each direction. Poisson's ratio was assumed to have a value of 0.20. The maximum bending moment was calculated as $0.14wL^2$ at the edge of the slab and $0.11wL^2$ at midspan.

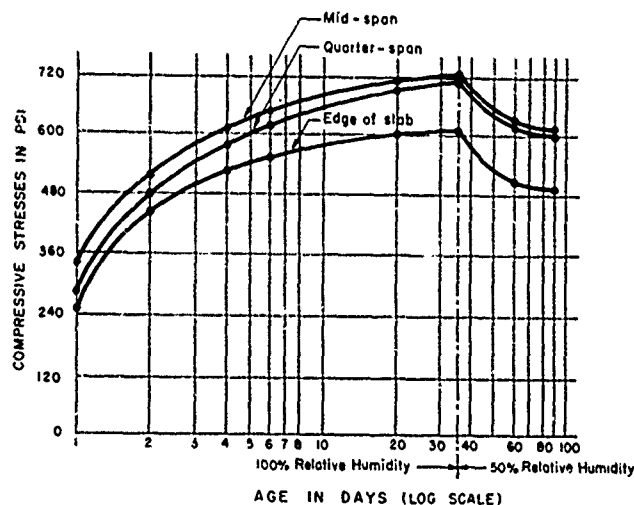
55. The compressive strength of concrete of the same mix design, cured in the same manner as the concrete for the slab, determined for 2- by 2- by 4-in. prisms cut from uniaxially stressed 2- by 2- by 12-in. bars and having 0.40 percent expansion at the end of fog-curing, was 6500 psi. The modulus of rupture was assumed to be 12 percent of 6500, or 850 psi, for use in theoretical calculations. Subsequent tests of 2- by 2- by 12-in. prisms, uniaxially restrained, after fog-curing and drying shrinkage, showed a modulus of rupture after removal of the restraint amounting to 1100 psi.

56. Using the calculated modulus of rupture of 850 psi and an effective prestress of 560 psi, the resisting moment of the slab at cracking was calculated as

$$M = \frac{850 + 560}{6} \times 2^2$$

or

940 ft-lb per ft width of slab



Lin and Klein, Reference 16.

Fig. 11. Compressive stresses in two-way concrete slab due to expansive self-stressing

The cracking load was computed as

$$940 = 0.14wL^2$$

or

$$w = 200 \text{ lb per sq ft at initial cracking}$$

Since the weight of the slab, 25 lb per sq ft, acts downward, the total upward air pressure required for cracking was computed to be $200 + 25$, or 225 lb per sq ft. The actual pressure measured at the appearance of first cracking was 260 lb per sq ft. Hence if a modulus of rupture of 1100 psi and a compressive strength of 580 psi had been used in the theoretical calculation the theoretical and experimental results would have checked exactly.

57. The ultimate resisting moment can be calculated approximately, assuming steel stress at 200,000 psi, as

$$\begin{aligned} M &= A_s f_s j d \\ &= 0.1424 \times 200,000 \times 0.80 \\ &= 22,800 \text{ in.-lb} \\ &= 1900 \text{ ft.-lb} \end{aligned}$$

Using the crackline theory,

$$\begin{aligned} w &= \frac{8 \times 1900}{5.83 \times 5.83} \\ &= 447 \text{ lb per sq ft, and} \end{aligned}$$

$$447 + 25 = 472 \text{ lb per sq ft at ultimate,}$$

whereas the actual observed pressure at the ultimate was

$$460 \text{ lb per sq ft}$$

58. The slab after test showed a crack pattern of highly symmetrical character. The symmetry of the crack pattern is believed to reflect for the most part the high degree of symmetry of prestress distribution in the concrete and in the steel, in the two directions of expansion and restraint.

59. One-way slab. The nominally one-way slab was fabricated using the same concrete-mix design as for the two-way slab. The overall

dimensions of the one-way slab were 8 ft in the long direction, 5 ft 3-3/4 in. in the short direction, and 3 in. in thickness. A wooden form was constructed with special arrangements for external vibration of concrete for the slab. No difficulties were encountered in placement, leveling, or finishing of the concrete. Vibration for placement was continued for 60 sec.

60. The slab was flooded with water for 2 days, raised free of the form, and placed in fog at 70 F. Fog-curing was continued to 14 days age. Stabilization of expansion occurred within this period for all practical purposes, the rate of expansion becoming very slow after 10 days. The slab was stored at 70 F and 50 percent relative humidity between 14 and 40 days age, then returned to fog at 70 F for 5 days prior to being tested under load.

61. High-tensile steel wires, 0.276 in. in diameter, anchored at both ends, were placed at 6-3/4 in. on centers in the longitudinal direction only. The ratio of steel to concrete area was 0.3 percent. In the transverse direction, five 3/8-in. locating bars of deformed structural steel were placed about 2 ft apart. These locating bars were used without end anchorage.

62. The expansion of the concrete at the center and edges of the slab is shown in fig. 12 for both the longitudinal and the transverse directions. In the longitudinal direction the maximum expansions were 0.44 percent at the center of the slab and 0.48 percent at the longitudinal edges. This is a 10 percent greater expansion at the center of the slab than that for the two-way slab, accounted for by the lower ratio of steel to concrete area of 0.30 for this slab as compared to 0.59 for the two-way slab. As can be expected, the expansions in the transverse

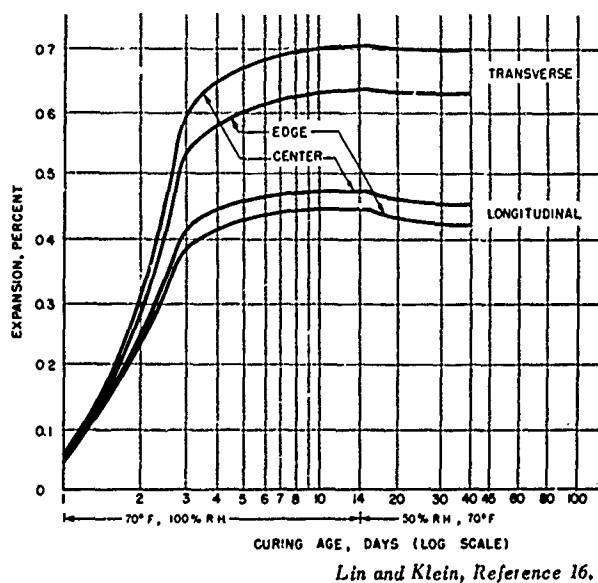


Fig. 12. Two-dimensional expansion of one-way concrete slab

direction, which was reinforced lightly with conventional steel without end anchorage, were substantially higher than those for the longitudinal direction, being 0.64 percent at the center of the slab and 0.71 percent at the transverse edges. It is apparent that the effect of bond in the transverse direction reduced transverse expansion to some degree. The expansion was about 60 percent greater in the transverse direction than in the longitudinal direction, whereas other test data indicate that in long members of small cross section with axial restraint only, the transverse expansion is 80 to 100 percent greater than that in the direction of restraint.

63. Shrinkage was low during the 26 days of drying at 70 F and 50 percent relative humidity, the net expansions at 40 days age being 0.43 and 0.45 percent in the longitudinal direction for the center and the edges of the slab, respectively, and 0.61 and 0.70 percent in the transverse direction for the center and the edges of the slab, respectively.

64. The tensile stresses in the steel are shown in fig. 13. The

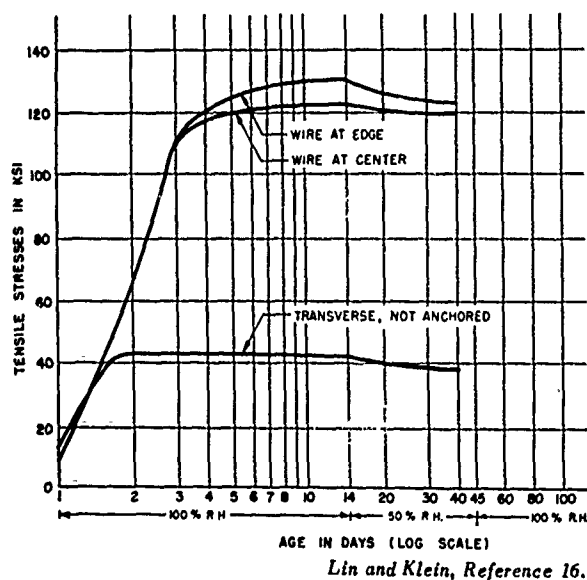


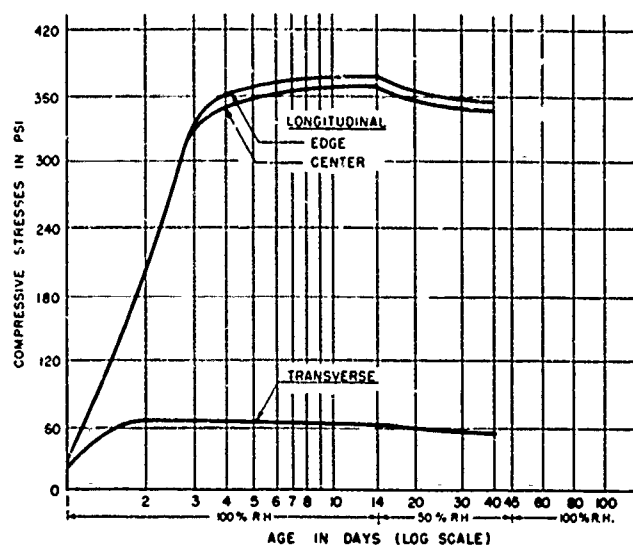
Fig. 13. Development of tensile stresses in steel of one-way slab due to expansive self-stressing

65. Relatively high tensile stresses were also developed in the transverse structural steel bars without anchorages. At 2 days age a stress of about 42,000 psi, and at 5 days age a maximum of 44,000 psi were reached. Between 5 and 14 days age, the stress decreased to

41,000 psi due either to slight amounts of slip or to yielding of steel.

66. The transverse steel appeared to have a very desirable effect upon the general behavior of the slab. It not only induced compressive stresses in the concrete in the transverse direction, but also reduced somewhat the transverse expansion of uniaxial elements.

67. Calculated compressive stresses in the concrete induced by the chemical prestressing are shown in fig. 14. The rates of stress increase



Lin and Klein, Reference 16.

Fig. 14. Development of compressive stresses in concrete of one-way slab due to expansive self-stressing

reflect, of course, the rates of stress increase in the steel. No significant difference occurred in the compressive stresses between the center and edges of the slab in the longitudinal direction. The maximum compressive stress achieved in the longitudinal direction averaged 375 psi, which was decreased to an average of about 355 psi due to shrinkage on drying. A compressive stress of about 65 psi was observed in the transverse direction of the slab

throughout the whole curing period after 2 days age.

68. For testing, the slab was simply supported along two edges, leaving a clear span of 7 ft 6 in. A uniformly distributed load was applied through the use of air pressure as in the testing of the two-way slab. In the testing, as the slab was loaded, progressive values of deflection and strain were observed. From the plotted load-deflection and load-strain curves it was inferred that microcracking could start as early as a live-load stress of 280 lb per sq ft when the curves began to depart from a straight line, whereas the actual cracking load was observed to be 300 lb per sq ft. The observed ultimate load was 400 lb per sq ft of air pressure.

69. Assuming an effective prestress in the concrete at the time of testing to be 360 psi, the modulus of rupture can be computed as shown

below, based upon the cracking load of 300-lb-per-sq-ft air pressure and weight of slab at 38.

$$\text{Net upward load} = 300 - 38 = 262 \text{ lb per sq ft}$$

$$\begin{aligned} \text{Maximum bending moment} &= \frac{wL^2}{8} \\ &= \frac{262 \times 7.5 \times 7.5}{8} \\ &= 1840 \text{ ft-lb} \end{aligned}$$

$$\begin{aligned} \text{Maximum tensile stress} &= \frac{6M}{bd^2} \\ &= \frac{6 \times 1840 \times 12}{12 \times 3 \times 3} \\ &= 1230 \text{ psi} \end{aligned}$$

$$\begin{aligned} \text{Modulus of rupture} &= 1230 - 360 \\ &= \underline{870 \text{ psi}} \end{aligned}$$

70. To compute the ultimate load, it can again be assumed that the steel developed an ultimate stress of 200,000 psi, while the lever arm can be approximated as 1.33 in. by applying the Whitney theory for a rectangular stress block in concrete of $0.85 f'_c$ with $f'_c = 6500$ psi. Thus, for $A_s = 10 \times \frac{0.06}{5.31} = 0.113$ sq in. per ft of slab, the ultimate moment per foot of slab is:

$$\begin{aligned} M &= A_s f_s Jd \\ &= 0.113 \times 200,000 \times 1.33 \\ &= 30,000 \text{ in.-lb} \\ &= 2500 \text{ ft-lb} \end{aligned}$$

71. At 400-lb-per-sq-ft ultimate air pressure, the tested maximum moment is:

$$\begin{aligned} M &= \frac{wL^2}{8} \\ &= \frac{(400 - 38) \times 7.5 \times 7.5}{8} \\ &= 2540 \text{ ft-lb} \end{aligned}$$

which agrees closely with the value of 2500 ft-lb calculated above and indicates the validity of the assumptions.

72. Major cracking occurred at midspan as expected for the type of support and loading employed in testing the slab to failure. One major crack occurred at a pressure of 300 lb per sq ft, at which time it was observed that loss of end anchorage had occurred to a considerable extent. Hence, no further cracking occurred on loading beyond the pressure of 300 lb per sq ft.

Hyperbolic paraboloid shell

73. An 8-ft-square hyperbolic paraboloid with a rise of 1.5 ft was fabricated with a concrete mix containing 7-1/2 sacks of portland cement and 2-1/2 sacks of expansive calcium aluminosulfate cement per cu yd of concrete, using a maximum aggregate size of 1/4 in. The membrane was 0.8 in. thick and the cross section of the edge beams was 3 by 3 in. High-strength steel wires of 0.105-in. diameter were used as reinforcement. The wires were spaced 2.5 in. each way, providing reinforcement in the amount of 0.43 percent. The edge beams were reinforced with four similar wires.

74. As in the case of the two slabs, expansion was stabilized at 0.4 percent, in this case at age 20 days, water-curing being used throughout. Water-curing was continued to 50 days age, and the shell was then subjected to drying shrinkage to 70 days age, at which time the shell was dimensionally stable for all practical purposes with a net expansion of 0.35 percent.

75. The shell was tested under uniform live load applied by air pressure, being supported both horizontally and vertically at two corners diagonally opposite. First crack occurred under a net load of 345 lb per sq ft, and the shell collapsed at a net load of 585 lb per sq ft.

76. The shell was fabricated as a graduate research project by John Choi, a graduate student in the Structural Engineering and Structural Mechanics Division of the Department of Civil Engineering at the University of California, Berkeley. Testing of the shell and analysis of the behavior of the shell under loading were carried on under the supervision of Professor Vitelmo V. Bertero.²⁰

Conclusions

✓ 77. Lin and Klein felt that the most significant conclusion to be drawn from these tests was that the structural behavior of such chemically prestressed concrete elements as pipes, slabs, and perhaps shells can generally be predicted by the usual elastic and plastic theories for structural analysis. In this instance, this conclusion is applicable only to the particular composition of expansive cements utilized in the fabrication of the structural elements involved. For this composition, the parameters involving expansion, shrinkage, stress, and strength relations had previously been established. Hence, sufficient data were available to predict and to control the behavior of the expansive concrete utilizing expansive components manufactured in the laboratory. The authors emphasized that the composition and manufacture of expansive cements are still in the research and development stage, particularly with respect to utilization in members having very high degrees of stress in steel and in concrete.

✓ 78. It is evident that further development is likely in the nature and properties of the expansive concrete which, while not detracting from the promise now shown in applications to chemical prestressing and shrinkage compensation, will require further thorough study of many factors not yet covered with respect to mechanical and structural properties of these concretes.

PART IV: RUSSIAN WORK

79. Mikhailov²¹ reviewed the status of work pertaining to expanding cements in the U.S.S.R. as of 1962 as a principal paper in the Fourth International Symposium on the Chemistry of Cements. His review described

...waterproof expansion cement, called WEC, ... developed in 1942. It is obtained by dry grinding of high alumina cement, gypsum, and artificial hydrocalumite (C_4AH_{13}). Its functioning is based on quick formation of high-sulfate sulfoaluminate (ettringite). It quickly develops high strength, provides full shrinkage compensation, sufficient expansion, and great watertightness. It is excellent for repair and restoration of concrete structures, and as a waterproof layer.

...stressing cement, called SC, is a more recent development, and research on it is continuing. It has three components: finely ground portland cement clinker, high alumina cement, and gypsum. Typical percentages are 66:20:14 when the portland cement has moderately high C_3A content. Use of a low percentage of water (25-30 percent) in 1:1 mortar gives good results under hydrothermic treatment (up to 100°C) after a day of natural hardening. Low-sulfate sulfoaluminate forms first. Recrystallization to high-sulfate sulfoaluminate in the already hardened mass causes expansion, with retention of the bond to reinforcing steel, thus stressing the latter. High strength, watertightness, and prestressing possibilities make stressing cement a valuable binder for prestressed construction.

Theories of chemical action are presented, and research developments are discussed. Methods of producing self-stressed piping are described and compared.

80. More extended excerpts from Mikhailov's review are included in Appendix B.

81. Budnikov²² stated that the addition of about 30 percent of gypsum to aluminous cement in the presence of a liquid phase results in a chemical interaction of gypsum with calcium aluminates to form a hydrosulfoaluminate, and that when hardening occurs under moist conditions an expanding cement of high impermeability to water is formed without decrease in strength. Using 25 percent anhydrite, a nonshrinking cement is obtained.

82. In water-cured samples of aluminous cement with 30 percent gypsum, about half the combined linear expansion takes place the first day. Samples 230 mm in diameter and 50 mm long were prepared from mortar, and samples 100 mm in length were prepared from concrete mixtures. The concrete contained 280 kg of cement, 170 l of water, 690 kg of building sand,

and 1300 kg of crushed granite. At an age of 3 days, the samples were impermeable to water under 8-atm pressure. It was found that gypsum-aluminous cement in rich mortars of 1:2 and 1:2.5 (by weight) compositions and in concrete with 377 kg/m^3 of cement and a water-cement (W/C) ratio of 0.45 is frost-resistant; in mortars and concretes of the consistency and composition stated the gypsum-aluminous cement withstood over 200 cycles of alternate freezing (at -17 to -22°C) and thawing (in water at $17 \pm 3^\circ \text{C}$) for 16 hr.

83. Trial determinations of the adhesion to reinforcing steel of concrete made with expanding cement were undertaken by the method of pressing down steel bars 14.4 mm in diameter and 125 mm in length. The concretes tested had a W/C ratio of 0.60. Each dimension of the concrete cubes tested measured 100 mm. In the case of air-curing, the average value of adhesion proved to be 64 kg/cm^2 , and in the case of water-curing, 40 kg/cm^2 .

84. The temperature rise during the hardening of expanding cement does not influence its strength. Tests showed that at 60 to 65°C , with alternate drying and saturating with water, the expanding cement was stable.

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PART V: STATUS OF KNOWLEDGE OF EXPANSIVE
CEMENTS AS OF 1 JULY 1963

85. Czernin,²³ in 1962, regarded expansive cements as still in the experimental stage, but observed that they may become of considerable interest in the future. He noted that they were composed of portland cement rich in aluminates, gypsum, and blast-furnace slag. The aluminates in the portland cement react with gypsum to form calcium sulfoaluminate; the slag "...is supposed to act as a stabilizer by which the intentionally produced gypsum expansion can be controlled and stopped altogether at a suitable stage." He adds "...since the extent of the expansion produced in this way is difficult to control, and the final stress produced in prestressing elements is not very high, this interesting special cement has so far been used only in certain special cases."

→ 86. Idorn²⁴ noted that research has been conducted on the role of calcium aluminate sulfates in concrete for more than 100 years. Most of this work has been based on the hypothesis that crystallization accompanied by volume increase of the "cement bacillus" was a major cause of expansion and concurrent disruption of concrete exposed to sulfate solutions, e.g. sea water. Later on, studies of the influence of the calcium aluminate sulfates on the initial setting of portland-cement paste also commenced. And most recently, successful efforts both in the U.S.S.R. and in the United States of America have proved that expansive forces ascribed to the crystallization of calcium aluminate sulfates can be controlled and utilized for prestressing of concrete members instead of external mechanical devices. This development may be said to reflect a remarkable range of opinions on the calcium aluminate sulfates. Once this sulfate crystallization was considered a common cause of rapid and severe deterioration, but today it is utilized as a means of manufacturing concrete according to the most advanced construction principles.

87. Admittedly such self-stressed concrete has not yet proved durable; but on the other hand, it might be possible that other detrimental agencies could, upon further research, be tamed and utilized. Today, expectations of such kind may with some right be stamped as banalities, and one might prefer the more limited question: To what extent are still

2
→ nonrevealed factors involved in the chemical reactions between aggregate particles and components of cement paste in concrete? Idorn further suggested that there appeared to be a need of renewed research on the lime-alumina-sulfate-water system, aimed at a more accurate description of the potentially expansive combinations of cements, admixtures, and particular rock types in aggregates, and with due regard also to the environmental exposure conditions, the structural qualities of concrete (e.g. permeability), and the construction principles. The need for the low- C_3A cements for concrete in sea water may be considered one subject of such studies, and the further development of self-stressing cements another. As a whole it is important to remember that the range of deleterious combinations within the outlined system is only a small part compared with the area of beneficial combinations. However, it should also be borne in mind that with deleterious combinations, exceedingly rapid and disastrous deterioration has been experienced in several cases.

88. The conservative viewpoint exemplified by the remarks of Czernin²³ and Idorn²⁴ quoted above may be contrasted with the apparently rather extensive use of expansive cements in practical engineering applications that were described by Mikhailov²¹ at the Symposium in which Czernin was also a participant. This viewpoint may also be contrasted with the increasing use of the materials developed by Klein and associates^{16,18,19} in experimental structures including full-scale paving projects. One of these⁶ was described in March 1963 as follows:

Connecticut's highway department takes bids this spring on a project that includes an experimental section of expansive concrete pavement. The section will be the first of its kind in this country.

The three-lane, 1500-ft-long section of Interstate 84 in East Hartford will use reinforced concrete that expands after it has been placed as a result of using an expansive cement made by combining bauxite with portland cement in the manufacture of the cement. Since expansion of the concrete places the reinforcing steel in tension, producing a pre-stressed slab, the pavement is said to be "self-stressing."

Departmental engineers point out that less concrete is required with this type of construction, since a thinner pavement can be used. Tentative plans call for the experimental section to be 6 in. thick, increasing to 9 in. in the outside 2 ft of each lane to permit the use of standard paving forms.

The engineers also believe that riding qualities of the new pavement will be better than the conventional design since transverse joints are spaced much farther apart (500 ft in the I-84 experiment).

Planned longitudinal steel will be 1/2-in.-dia, seven-wire strand (ASTM 416), placed at one-half pavement depth with 14-in. nominal spacing. Outside strands will be 3 in. from each edge of the lane. Strands will extend the full length of each 500-ft section and be held taut throughout paving operations. Transverse reinforcement will be No. 7 bars spaced 24 in. c-c and placed alternately above and below the strands with the bars bent 90 deg at the ends to form hooks.

There will be standard keyways where lanes abut, but no tie bars or bonding between slabs. High quality concrete of low slump will be used. In order to minimize friction between the pavement and the subgrade, the contractor will cover the subgrade with about 1/2 in. of bituminous concrete and cover this layer with two layers of polyethylene sheeting before placing concrete.

Present plans call for reinforced concrete sleeper blocks, 20 ft long and 7 in. thick, to be placed with their top surfaces at subgrade elevation. The sleepers will be centered beneath the joints at the ends of the experimental section and at the joints between the 500-ft slabs.

Centered in each block and extending across the roadway will be a 12-in.-wide flange beam section cut in lane widths. Top surface of each of these beams will be at finished grade. The top surface of each sleeper block will be covered with a two-layer polyethylene bond breaker.

As the pavement is built, the contractor will bulkhead the end of each slab 7 ft 3 in. from the center of the transverse beam. The strands will extend through the bulkhead, so there will be space in which to grip and hold the strands taut during concreting operations. They will also place, through the bulkhead and parallel to the strands, deformed steel bars that will extend at least 3 ft on each side of the bulkhead.

After the concrete has been placed, it is expected to expand enough to reduce the space from 7 ft 3 in. to about 6 ft. Later this remaining space over the sleeper will be filled with conventional reinforced concrete.

Because of the thickened-edge design of the proposed pavement, it is planned to keep the top surfaces of the sleeper blocks uniformly 9 in. below finished grade. For this reason, each expansive concrete section will have a transition section; the plan is to make the 9 ft closest to the bulkhead 9 in. in uniform thickness, changing to the 6-in. slab with thickened edges in another 3 ft.

The Bureau of Public Roads is contributing 90% of the cost

and also providing engineering support. T. Y. Lin and Associates, Van Nuys, Calif., consultants, in joint venture with contractors C. W. Blakeslee and Sons of New Haven, Conn., and the Permanente Cement Co. of Oakland, Calif., are collaborating in the experiment.*

89. Other experimental pavements were placed in California in the summer of 1963.²⁵ Interest in expanding cements has also recently been manifest in other countries. Chopra and Rai²⁶ have published a paper in which:

The suitability of the following methods of preparing expansive cements is discussed critically, with supplementary experiments conducted by the authors: (a) Portland cement mixed with CaSO_4 and the dried hydration products of lime and burnt kaolin (Budnikov and Kosuireva^[15]); it is considered preferable to mix dry predetermined quantities of the four constituents. (b) Portland cement mixed with granulated high- Al_2O_3 slag, lime, and gypsum; these cements are not considered truly expansive even when stabilized with 10-15 percent of high- Al_2O_3 cement. (c) Portland cement mixed with bauxite and CaSO_4 instead of with a sulfo-aluminate clinker; the expansive action of these cements is inconsistent and also very sensitive to the quality of the materials and method of preparation. (d) "Self-stressing" cements made from a mixture (74:14:12) of portland cement, gypsum and high-alumina cement cured 6 hr at 70° (Mikhailov^[17]); the portland cement should optimally contain C_3S 48, C_2S 27, C_3A 11 and C_4AF 8 percent, but expansive effects are strongly influenced by the amount of mixing water and by the nature of the aluminous component; that is, kaolin, slag and bauxite are inferior to high-alumina cement. The mechanism of expansion and the role of stabilizer are discussed; more information is needed to develop a more rational method of preparing expansive cement.

90. An application of expansive cement to grouting was described by Polivka and Klein.²⁷ This application is similar in many respects to that investigated by the WES⁵ and mentioned by Cassidy.⁷ The report by Polivka and Klein included the following:

* A news item entitled "Self-Stressing Concrete Slab Tested in Pilot Installation" appeared in Pit and Quarry for December 1963, p 40, which stated that in June 1963 a prototype slab of self-stressing concrete was made at the Prestress Division of C. W. Blakeslee and Sons, Inc., Hamden, Conn.

Studies were made of bond strength characteristics of grouts containing an expansive constituent. In one set of grouts, aluminum powder was utilized to produce expansions prior to setting. In the other set of grouts, a calcium sulfoaluminate expansive component caused expansions of the grouts subsequent to setting. For both cases there were studied neat-cement grouts and sand-cement grouts.

For grouts containing aluminum powder, expansion was terminated within about 3 hours after mixing. For grouts containing calcium sulfoaluminate expansive component, termination of expansion for all practical purposes was within 5 to 7 days after grouting.

Test results indicate that the grouts containing the calcium sulfoaluminate expansive component develop much higher bond strength than the grouts containing aluminum powder. The ultimate bond strength of a neat-cement grout containing 30 percent of expansive component by weight of cementing material was more than double the bond strength of a grout containing aluminum powder in the amount 0.03 percent by weight of cementing material.

The greater bond strength of grouts containing the expansive component is due to the compressive self-stress developed in the grout which is restrained from expansion in the prestress cable. This compressive self-stress increases the frictional resistance of the wire.

Sand-cement grouts showed higher bond strengths than the neat-cement grouts. It is believed that this difference in bond strength is due to the greater frictional resistance of a sand-cement grout as compared to a neat-cement grout.

...it appears that the use of grout mixtures containing the calcium sulfoaluminate expansive component used in this investigation will produce considerably higher bond strengths than those obtained with conventional grouts.

INTRODUCTION

When the tendons of post-tensioned prestressed concrete members are to be bonded to the concrete, the prestressing cables are usually grouted with a cement grout. The grouting not only provides the bond between steel and concrete but also protects the steel against corrosion. Depending on the size of the prestressing cables, there is injected either a neat-cement grout or a sand-cement grout.[28] These grouts usually contain a small amount of aluminum powder which causes the grout to expand during the first few hours after mixing and insures more complete filling of the cable ducts.[29]

Recently there was developed at the University of California an expansive material which causes grout to expand after setting of the grout has taken place. This

material is a calcium sulfoaluminate which when used with portland cement produces a cementing material to develop self-stress in concrete members^[18,19]. Properly designed concrete members can be self-stressed (compression in concrete and tension in steel) by the use of this material to desired practical stress levels through adjustment of mix proportions and amount of expansive component. The reaction causing the expansive forces is completed within 5 to 7 days after casting.

In this investigation, the expansive calcium sulfoaluminate component was used as one of the constituents in neat-cement grouts and in sand-cement grouts. Whereas the use of aluminum powder helps to insure more complete filling of the cable ducts, the use of a component which causes expansion after setting will improve the bond strength. Reported herein are the results of an investigation in which the bond strength characteristics of the two types of grouts are compared.

TEST PROGRAM

Grout Materials and Mix Proportions.

Since the main purpose of this investigation was to determine the effect on bond strength of a grout which expands after setting as compared to a grout expanding prior to setting, the test program included essentially two principal grout compositions, namely: (1) grouts containing an expansive component (calcium sulfoaluminate) which expand after setting^[18,19] and (2) grouts containing aluminum powder which expand prior to setting^[29,30]. The bond strength was determined for both neat-cement grouts and for sand-cement grouts. Altogether six grout mixtures were employed, three neat-cement grouts and three sand-cement grouts. The mix proportions of these six grout mixes are given in the following tabulation:

Grout Mix	Type of Grout	Cementing Material, % by weight			
		Portland Cement	Fly Ash	Expansive Component	Aluminium Powder
A	Neat Cement	80	20	--	0.03
B		80	--	20	--
C		70	--	30	--
D	Sand Cement (1:1 by wt)	80	20	--	0.03
E		80	--	20	--
F		70	--	30	--

Grout mixtures A and D which contained 20 percent of fly ash and 0.03 percent of aluminum powder by weight of cementing material (cement plus fly ash) were selected as being representative of the types of grouts that are considered to be appropriate for grouting of prestress cables. The fly ash, representing a typical suitable finely divided pozzolanic material was employed

to reduce the tendency towards bleeding and segregation of the grout and to improve the pumping characteristics of the grout. [29] Cementing material hereafter refers, as the case may be, either to cement plus fly ash or cement plus expansive calcium sulfoaluminate component.

All grout mixtures contained a commercial water-reducing retarder in the amount of 0.20 percent by weight of cementing material. The use of a water-reducing retarder in grouts will reduce their water content for a given consistency, will reduce any tendency towards premature stiffening, and will retard the setting of the grout. All of these properties are desirable for grouts to be employed for grouting of prestress cables. [29]

The sand employed in the sand-cement grouts (1:1 by wt) was a fine river sand practically all passing 30-mesh sieve and having a fineness modulus of 0.76. The gradation of this sand was as follows:

Sieve Size, U. S. Std	16	30	50	100	200
Percent Passing	100	98	87	39	9

The water-cementing material ratio of grouts was adjusted until the desired consistency was attained. The mixing procedure and the method of measurement of consistency by the "Flow Cone Apparatus" was the same as that described in references [29] and [30]. Essentially the consistency is determined as the time required for a given volume (1725 ml of grout to flow from a cone-shaped vessel through a discharge tube 1-1/2-in. long and 1/2-in. in diameter. This time of efflux of the grout, in seconds, is called the "Flow Factor."

The free expansions of the grouts were also measured. For the grouts containing aluminum powder (grouts A and D) the expansion characteristics of the fresh grout were determined and the expansion expressed as percentage of the original grout volume. Details of the expansion test are also described in references [18] and [19]. Since the free expansion of these fresh grouts terminated at about 3 hours after mixing, the test was discontinued at this age.

Grout Mix	Cementing Material (a) (by weight)	W/C, by Wt	Bond Stress, psi ^(b)		
			At First Slip Observed at Unloaded End	At 0.01-in. Slip of Loaded End	Ultimate
NEAT-CEMENT GROUTS (Consistency Factor 22 sec)					
A	80% C + 20% F + Al	0.30	65	200	210
B	80% C + 20% E, C	0.34	120	270	320
C	70% C + 30% E, C	0.34	240	380	460
SAND-CEMENT GROUTS (Consistency Factor 28 sec)					
D	80% C + 20% F + Al	0.49	95	260	270
E	80% C + 20% E, C	0.52	170	350	490
F	70% C + 30% E, C	0.53	350	480	510

(a) C = portland cement, ASTM type I.

F = fly ash.

E, C = expansive component - calcium sulfoaluminate.

Al = aluminum powder, 0.03 percent by weight of cementing material.

(b) High strength steel wire 0.196 in. (5 mm) dia, 9-in. embedment.

For the grouts containing the expansive component, the free expansion characteristics of the hardened grout could not be determined since the large expansions produced by this component would severely disrupt a hardened grout bar, making measurements meaningless. As reported by Klein, Karby, and Polivka,^[19] the use of this expansive component produces free expansions of about 1 to 3 percent (depending on many factors described in their paper) for concretes of substantially lower cementing-material content than for grouts employed in these tests.

Properties of Grouts.

Water content of the grouts was gaged to produce a Flow Factor of 22 seconds for the neat-cement grouts and 28 seconds for the sand-cement grouts. The water-cementing material ratio of the neat-cement grouts ranged from 0.30 to 0.34 and for the sand-cement grouts from 0.49 to 0.53 by weight. The use of 0.53 percent of aluminum powder caused a 12.5 percent free expansion of the neat-cement grout (grout mixture A) and an 8.0 percent expansion of the sand-cement grout (grout D). The aluminum powder used was a 100-mesh leafing type having a specific surface of 31,000 sq cm per gram.

Bond Test.

The bond stress and the slip characteristics were determined on a high-strength 0.196 in. (5 mm) diameter steel wire which was grouted in a vertical position over a 9-in. length inside a 1-1/4-inch diameter steel tube. The tube, which was a standard flexible prestress cable hose was embedded inside a 9-in. concrete cube.... The cubes were made of concrete having a compressive strength of 6,000 psi at 28 days.

Prior to being grouted, the wire was centered inside the 1-1/2-in. steel hose by passing it through the centers of rubber stoppers placed at each end of the tube. The bottom stopper was also provided with a 3/8-in. diameter injection tube, and a similar tube was installed in the top stopper to act as an overflow for the grout.... After the 1-1/4-in. steel tube was completely filled with grout, the two openings were sealed and remained sealed for 7 days, the age at which the bond test was performed.

The bond test itself was carried out following the same procedure as the standard procedure for determining the bond characteristics of concretes, ASTM Designation C234.³¹...

The high-strength wire (0.196 in. or 5 mm in diameter) had an ultimate tensile strength of 240,000 psi

and a modulus of elasticity of 29.5×10^6 psi.

TEST RESULTS

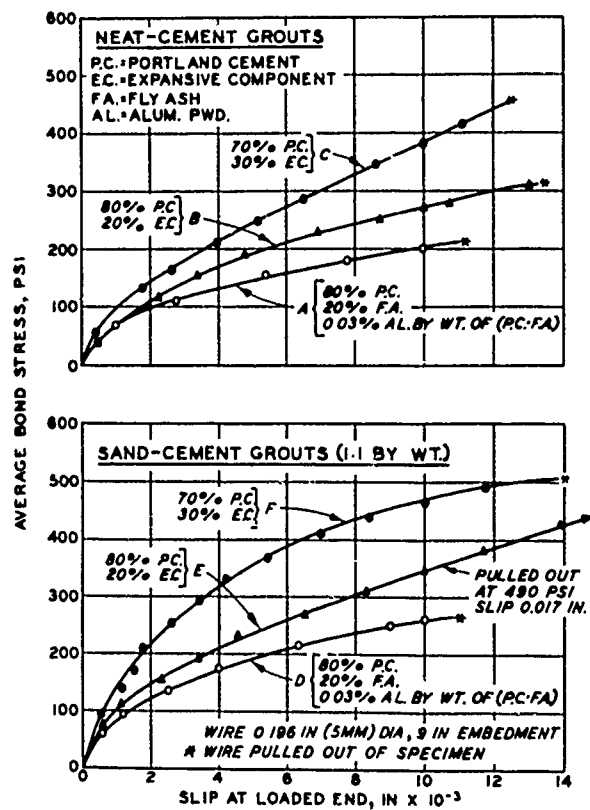
The bond strength and slip characteristics of grouted wire were determined at age 7 days in three specimens for each one of the six grout mixtures. The test results are given in the tabulation of p. [39] and in fig. [15].

The grout mixtures containing the expansive calcium sulfoaluminate component had a considerably higher bond strength than the corresponding grouts containing aluminum powder. For the neat-cement grouts, for example, the grout containing 20 percent of calcium sulfoaluminate expansive component by weight of cementing material (grout B) had an ultimate bond strength of 52 percent higher, and the one containing 30 percent of expansive component (grout C) 120 percent higher than that of the grout containing aluminum powder (grout A). Similarly, the bond stress at 0.01 in. slip of the loaded end and at the first observed slip of the unloaded end was considerably higher for the grouts containing the calcium sulfoaluminate expansive component than for the grout containing aluminum powder. This superiority of the bonding quality of grouts containing the expansive component is to be anticipated since the expansion of the grout after hardening, which is restrained by the concrete member, will develop a self-stressing condition in which the grout is in compression and is forced against the prestress wire. As described by Klein, Karby and Polivka.^[19] The magnitude of self-stress might be of the order of 1,000 to 2,000 psi. Since the bond of a smooth prestress wire is purely a frictional phenomenon, an improvement of the frictional resistance under such conditions of self-stress would be expected.

It is pointed out that these tests are of a limited scope. It can be anticipated that bond and slip characteristics can further be improved by increase in the amount of calcium sulfoaluminate expansive component above the 30 percent employed in these tests. It is likely also that further improvement could be obtained for grouts containing aluminum powder by increasing the percentage above the 0.03 here employed.

The use of sand-cement grouts produced higher bond strengths than those for the corresponding neat-cement grouts. For example, the sand-cement grout containing 20 percent calcium sulfoaluminate (grout E) had an ultimate bond strength 53 percent higher than that of the corresponding neat-cement grout (grout B). The greater frictional resistance of a sand-cement grout as compared to that of a neat-cement grout is probably responsible for the higher bond strength.

Measurements taken on the unloaded end of the prestress



Lin and Klein, Reference 16.

Fig. [15]. Slip of grouted high-strength wire and corresponding average bond stress at age of 7 days

wire showed that the bond stress at which the first slip of the wire was observed is closely related to the ultimate bond strength. The higher the bond strength, the greater the bond stress needed for the free end of the wire to slip. Again, a higher proportion of calcium sulfoaluminate component would probably enhance performance.

Figure [15], in which are plotted the slip of the loaded ends during the bond tests, clearly illustrates the results discussed above. These curves represent the average of data obtained on three bond specimens. Variation between individual specimens was plus or minus 15 percent from the average plotted. The values at which the loaded end slipped 0.01 in., given in the previous tabulation, were obtained from these curves.

91. Subsequent to the completion of the preparation of this manuscript Dr. Shu-t'ien Li, Professor of Civil Engineering, South Dakota School of Mines, informally made available for study a manuscript he had prepared entitled "The Revealing Expansive-Cement Concretes."* He gave permission to quote extracts from it for inclusion in this summary. A number of such extracts follow:

Expansive cements and concretes, though they are seemingly new artificial engineering materials, have had a long history of development. During the past 74 years, there have been recurrent efforts toward evolving expansive cements. However, successful endeavors in producing such cements and their widening applications to controlled expansive concretes have only occurred within the last 15 years.

In 1949, it was ascertained by F. Ferrari that a controlled formation of expansive sulfoaluminate will occur only in a medium supersaturated with respect to calcium ions and maintained at supersaturation during the formation of this salt.

Expansive cements were made [at the Portland Cement Association] by mixing portland cement, calcium aluminate cement, and gypsum in varying proportions, and were thus similar to the "stressing cements" used in U.S.S.R. In contrast to U.S.S.R. expansive cements where the mixtures were produced by intergrinding, the PCA expansive cements were, however, produced by simply blending commercial portland cement, calcium aluminate cement, and gypsum in a concrete mixer just prior to the addition of aggregates and water. The gypsum used was of reagent quality. Using differently blended mixtures by varying portland cement from 42 to 80 percent, calcium aluminate cement from 4 to 50 percent, and gypsum from 4 to 20 percent, PCA researchers investigated the effects of

* Published as "Expansive Cement Concretes - A Review." Journal of the American Concrete Institute, Proceedings, vol 62, No. 6, June 1965, pp 689-706. (In the 3d line from the bottom on p 689, as published, the values "8" and "3.6" are interchanged.)

composition, and of time and temperature of cure, on mortar strength, free expansion, shrinkage, and development of stress in restrained specimens.

The PCA studies have shown that free expansions of several percent may be produced by expansive cement mixtures of portland cement, calcium aluminate cement, and gypsum. The magnitude of the expansion may be controlled by the composition of the mixture and by the temperature of cure.

In the PCA studies, expansive mortars that were cured sufficiently to complete the expansion and were then allowed to dry in an atmosphere of 50 percent relative humidity shrank about the same amount as conventional mortars, that is, 0.1 to 0.2 percent. However, as the expansion before shrinkage may be a few percent, a considerable net expansion is available for inducing stress in restraining steel.

Although conditions of tests were necessarily somewhat different, a scrutiny of test results of U.S.S.R., UC, and PCA expansive cements shows, in general agreement, the following:

- (1) Free expansions of several percent may be produced by either of these variant products.
- (2) The lower the water-cement ratio of the mix is, the greater will be the subsequent expansion.
- (3) Unrestrained expansion adversely affects compressive strength. However, if the expansive concrete or mortar is adequately restrained, high compressive strength can be attained.
- (4) All the three variant products can induce compressive stresses in expansive concrete or mortar by uniaxial restraint. However, such induced maximum compressive stresses were considerably higher in the expansive concrete for the UC tests than were the corresponding mortar stresses for the U.S.S.R. and PCA tests. The UC tests reported a maximum induced compressive stress of 1200 psi versus 700 psi for the U.S.S.R. tests and 530 psi for the PCA tests.

It must be realized that the composition and manufacture of expansive cements, the fabrication of expansive-cement concrete members, and chemical prestressing are all still in the research and development stage. Though the writer has unquestionable faith to envisage a multitude of potentially very promising applications, he is obliged to encourage further thorough explorations which seem necessary before expansive concretes can be used in a routine fashion. Such further studies obviously appear to lie in the following areas:

- (1) Determination of optimum compositions, proportions, and fineness of components of the expansive cements.
- (2) Determination of optimum proportioning and curing, with the objective of producing expansive concretes having predetermined optimum characteristics.
- (3) Determination of optimum utilization of expansive concretes in members having high degrees of stress in steel and in concrete.
- (4) Evaluation of loss of steel stress as affected by shrinkage and creep of concrete, and slippage of reinforcement.
- (5) Determination of other factors, so far not yet covered, with respect to mechanical and structural properties of expansive concretes.
- (6) Formulation of design criteria for expansive-concrete mix and expansive-concrete members with respect to desired degree of chemical prestressing and shrinkage compensation.

California Experimental Sections

According to D. L. Spellman, two experimental sections were installed in 1963 in California: one for the construction of a portion of the Antelope Valley Freeway near Palmdale in District VII, and the other for converting U.S. 99, near Lodi in District X, to freeway status. For the Antelope Valley Freeway section two cement factors were used, 6 and 6-1/2 sacks per cu yd, while a single cement factor was used in all units of the Lodi section.

Due to comparatively less expansive cement used, the results of these early experimental sections have not been striking. After 58 days, following removal of curing membrane on the Antelope Valley Freeway section, the average distance between cracks in the expansive-cement pavement units was 60 ft, while the average in the control units was 56 ft; the average distance between cracks for the air-entrained units was 48 ft, while the average for the nonair-entrained units was 70 ft. In the Lodi section, after about three weeks of natural drying following the end of the curing period, the average distance between cracks in the expansive-cement pavement units was 68 ft, while the average in the control units was 65 ft. Gauge readings showed that vertical expansion was greatest, transverse movement was intermediate, and longitudinal movement was almost nil. Appearing to the writer, these early results would, however, indicate:

- (1) That a larger percentage of the expansive component could have been used;
- (2) That friction to expansion between the pavement and

its subbase might have not been reduced to the minimum;

- (3) That more full control of transverse movement would help to develop more longitudinal compressive stress for the same volume change of expansive concrete;
- (4) That the nonair-entrained concrete may have had much less drying shrinkage; and
- (5) That end anchors alone would be sufficient for longitudinal restraint, and no resort to lugs cut into the subgrade would be needed, as measurements and analysis of strain data at the Antelope Valley section had shown.

The Blakeslee Pilot Slab

On June 14, 1963, a prototype slab was cast at the Prestress Division plant of C. W. Blakeslee and Sons, Inc., at Hamden, Conn. This slab was constructed primarily to furnish information to the State of Connecticut Highway Department, which had scheduled to construct a full-size experimental pavement, using self-stressing concrete, near Glastonbury, Conn., in the fall of the same year.

Originally made for another purpose than constructing a prestressed slab, the expansive cement did not contain as much of the calcium sulphoaluminate as would be required for the desired expansion. Consequently, it was necessary to use ten sacks of cement (less expansive component) per cubic yard on this pilot project as compared with only about 7 sacks of cement (more expansive component) on the later Connecticut experimental pavement.

The mix design consisted of 940-lb expansive cement, 940-lb sand, 1,180-lb 1-1/4-in. traprock, 740-lb 1/2-in. traprock, 2-1/2-oz. Darex per cu yd, 40-oz. plastiment per cu yd, and 300-lb water. The concrete was given a slump of 3 to 4 in. due to hand methods versus a desired slump of 1 to 1-1/2 in. if finishing machine and spreader were available. Pouring was onto wetted forms and polyethylene sheeting. A double layer of such sheeting was placed over 1-in. layer of bituminous concrete laid over a compacted subgrade of spoil and quarry floor. Ambient temperatures were between 60 and 75 deg F.; the temperature of the concrete never exceeded 90 deg F.

Longitudinal reinforcement for the slab was provided by twelve 1/2-in. and six 3/8-in. diameter prestressing strands conforming to ASTM Standard A-516-59 T. The strands were spaced 9 in. on centers over the width of the slab, anchored to steel wide-flange beams embedded at the midpoint of end sleeper slabs. Transverse reinforcement was provided by No. 4 and No. 5 deformed bars spaced 8 in. on centers. The

transverse steel was alternated over and under the longitudinal steel and wire-tied to the strands. This heavy transverse steel was used to limit expansion in the transverse direction.

Finished dimensions within the forms were 185 ft 6 in. long, 13 ft 4 in. wide, and 6 in. deep. Sufficient gap was left between the end form and the steel wide-flange beam anchorage to allow for the expansion of the concrete.

After three days, measurements showed that the concrete had expanded 0.225 ft at one end and 0.275 ft at the other, an expansion of 0.27 percent over the original length.

Compression tests on cores from the pavement averaged 2,882 psi ranging from 1,855 to 3,940 psi, all corrected to a 7-day value. No cracks were evident on the surface or sides when the forms were removed. The slab was loaded with metal casting forms on the seventh day, and prestressed beams were cast on top of the 8-day-old slab.

This experimental pilot test slab at the Blakeslee plant demonstrated that the idea of using a self-stressing concrete with steel cables is a practical method of obtaining prestressed slabs at a minimum cost. Except the need of having equipment to start fog curing as soon as the slab surface is finished, the technique of using expansive cement differs very little from the ordinary practice.

The Connecticut Test Section

Connecticut's highway department had a 1,500-ft-long experimental section of expansive-cement concrete pavement built in 1963 on Interstate 84 in East Hartford. In its manufacture, the expansive cement was made by combining bauxite with portland cement. Engineers of the department claimed that (1) less concrete would be required with this type of construction, since a thinner pavement of 6 in. thick could be used, (2) riding qualities of the new pavement would be better than the conventional design since transverse joints would be spaced as farther apart as 500 ft in the I-84 experiment.

Longitudinal steel of 1/2-in.-dia, seven-wire strand (ASTM 416) was placed at one-half pavement depth with 14-in. nominal spacing and outside strands 3 in. from each edge of the lane. Strands were extended the full length of each 500-ft section and held taut throughout paving operations. Transverse reinforcement of No. 7 bars were spaced 24 in. c-c and placed alternately above and below the strands with the bars bent 90 deg at the ends to form hooks.

Standard keyways only were provided where lanes abut, with no tie bars nor bonding between slabs. The concrete used was of high quality and low slump. To minimize friction between the pavement and the subgrade, the latter was first

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covered with 1/2 in. of bituminous concrete and then two layers of polyethylene sheeting before placing concrete.

Reinforced concrete sleeper blocks, 20 ft long and 7 in. thick, were placed with their top surfaces at subgrade elevation. They were centered beneath the joints at the ends of the experimental section and at the joints between the 500-ft slabs.

Anchorage of strands was provided by 12-in. wide-flange beam sections extending in lane widths and centered in each block, with top surface at finished grade. The top surface of each sleeper block was also covered with two layers of polyethylene bond breaker.

The end of each slab was bulkheaded 7 ft 3 in. from the center of the transverse beam. The strands were extended through the bulkhead, providing space to grip and hold the strands taut during concreting operations. Through the bulkhead and parallel to the strands, deformed steel bars were placed extending at least 3 ft on each side of the bulkhead.

It was expected that after the concrete has been placed, the space of 7 ft 3 in. would be reduced to about 6 ft. This remaining space was later filled with conventional reinforced concrete.

Due to the tendency of the type of expansive-cement concrete used in the experimental section to set rather rapidly, difficulty was experienced in the finishing operations. The pavement texture, therefore, is slightly different from the adjacent conventional pavement. However, this phenomenon has since been overcome technically.

The Bureau of Public Roads contributed 90 percent of the cost and also provided engineering support.

As to service performance, reliable information has not become available because as of July 6, 1964 the highway has not been opened to traffic.

APPLICATION AND TESTS OF SHRINKAGE-COMPENSATED-CEMENT CONCRETE

Folded-Plate Roof Construction

The year 1963 also witnessed the application of a new shrinkage-compensated cement to concrete roof construction to eliminate shrinkage cracks. The 100 x 43-ft folded-plate roof was cast in place for a two-story branch office building of Midvalley Savings and Loan Association, in Yuba City, Calif.

Staggered columns carry 10 kite-shaped folded plates, with maximum width of 18 ft, five pointing toward one long wall and five toward the other. Each kite-shaped folded plate is supported by three 12 x 12-in. reinforced concrete columns, one support being under the tail of each kite, the other two under the corners 18 ft apart at the opposite wall. The fourth

corner cantilevers 6 ft beyond the exterior wall.

The plates are 6 in. thick where they join the columns but taper to 3 in. at the top of their 5-ft rise.

Typical roof reinforcing consists of No. 5 bars spaced 1-3/4 in. c-c and No. 3 bars 9 in. c-c.

A mixture of 86 percent portland-cement component and 14 percent expansive-cement component was selected for the roof. This blend provided enough expansion to stretch the reinforcing bars by about 0.1 percent. The concrete was a low-slump mix. Specifications call for concrete strength of 3,000 psi in 28 days.

Except for the use of shrinkage-compensated cement, this concrete roof construction followed the normal concreting practice. However, counting on the crack-free concrete to waterproof itself, the designers did not specify a waterproofing compound.

In the eight months since construction was completed, the roof had remained watertight, according to a published release in January 16, 1964. After drying, the concrete had only five hairline cracks. Its engineers believe that they could have been caused by finishing touches during construction, and they consider that the critical period of this prototype field test has passed.

Lightweight Concrete Roof Construction

In the course of obtaining approval from the Los Angeles City Department of Building and Safety for experimental use of shrinkage-compensated cement (Chem Comp) in lightweight concrete roof construction in a two-story commercial building with roof parking, laboratory investigations were undertaken in 1963 by Raymond G. Osborne Laboratories, Inc. of Los Angeles at the request of Concrete Research and Development Corporation. The main concern was whether shrinkage-compensated-cement lightweight concrete would develop adequate strength.

The Chem Comp cement had been made by intergrinding 14 parts expansive component with 86 parts Cushenbury Type I, II low alkali cement. As a control, a trial mix (No. 1) for a nominal 4,000-psi concrete was made using the said low alkali cement (585 lb). Two Chem Comp mixes were made, one (No. 2) containing the same amount of finished cement (585 lb) as the control mix and the other (No. 3) containing 14 percent more finished cement (665 lb). Finally, a second control mix (No. 4) was made containing 14 percent more low alkali cement (665 lb) than the first. The average concrete weight of each of the four different mixes was slightly less than 121 lb per cu ft, all fine and coarse aggregates, free and absorbed water, admixture, slump, and air content being very nearly the same.

At 28 days the compressive strengths showed the following satisfactory results:

Mix No.	1	2	3	4
Comp. Strength (psi)	5,500	4,765	5,135	6,015
Secant Modulus of Elasticity at 28 days (1,000,000 psi)	3.107	2.914	3.023	3.063

At 41 days, concrete of mix No. 1 had a shrinkage of -0.035 percent, while concrete of mix No. 3 had retained an expansion of +0.031 percent.

Approval was given to go ahead. The roof was post-tensioned in two directions to provide watertightness. The roof slab was placed in two approximately equally sized sections, one section with Chem Comp-cement lightweight concrete and the other portland-cement lightweight concrete. The dimensions of each section were roughly 148 ft by 58 ft, with the same nominal slab thickness of 6 in. The Chem Comp section contained a re-entrant corner where the ramp met the roof. Curing was by sprayed-on curing compound.

The Chem Comp concrete was made of mix No. 3. Three job-cast standard 6 X 12-in. test cylinders and three cores cut from the slab at each age showed average compressive strengths as follows:

Job-Cast Cylinders		Cores Cut from Slab	
Age (days)	Av. Comp. Strength (psi)	Age (days)	Av. Comp. Strength (psi)
28	5,346	29	4,735
60	5,877	293	4,787
90	6,090		

Through age six days, when the roof was post-tensioned for both sections, no cracks had appeared at any location of the shrinkage-compensated-cement roof deck, though there was a re-entrant corner; while in the companion half of the roof deck, with no re-entrant corner, placed with portland-cement concrete, a regularly spaced pattern of drying shrinkage cracks was visible. Internal reinforcement and all placing and finishing operations were alike and the same as in normal concrete practice in both cases.

From the above laboratory tests and field observations, engineers of the Concrete Research and Development Corporation have drawn the following conclusions:

- (1) Normal strengths can be obtained in normal concrete mixes using shrinkage-compensated cement.
- (2) Strengths obtained in shrinkage-compensated-cement concrete trial mixes show a direct relationship with the amount of portland cement in the mix.
- (3) The advantages of shrinkage-compensated cement can be obtained in the field without departure from standard engineering and construction techniques and practices.

STEERING GEARS OF EXPANSIVE CEMENTS AND CONCRETES IN U.S.

In the U.S. at the present (1964) a spectrum of Federal, state, academic and institutional, professional, and industrial interests and their steering mechanisms in advancing the technology of expansive cements and concretes may be viewed from the following:

- (1) The National Science Foundation is supporting "A Basic Study of Expansive Cement and Expansive Concrete" (P-11493, GP-616) with a grant of \$114,900 for two years in Fiscal 1963 and 1964 by Vitelmo Bertero and Milos Polivka in the Institute of Engineering Research, University of California at Berkeley.
- (2) In the Division of Highways of the State of California Department of Public Works, its Materials and Research Department is continuing field performance observations on the Palmdale and Lodi expansive-concrete-pavement test sections respectively on the Antelope Valley and U. S. 99 Freeways. Concurrently in New England, the State of Connecticut Highway Department continues observations on the field performance of its East Hartford test section on Interstate 84, of expansive-concrete pavement to which the Bureau of Public Roads of the U.S. Department of Commerce contributed 90 percent of the cost.
- (3) In the Division of Structural Engineering and Structural Mechanics, University of California at Berkeley, several faculty and research members, notably T. Y. Lin, Alexander Klein, Vitelmo Bertero, and Milos Polivka, are continuing their research, both basic and applied, in the field of expansive cements and concretes. Coincidentally, another advanced study and research group led by Shu-t'ien Li and William V. Coyle on the faculty of the Department of Civil Engineering at South Dakota School of Mines and Technology, delves in the applied technology of translating scientific and technological findings in expansive cements and concretes into operative and optimum criteria for use in design and construction practices. Their research and development mission

is aimed at filling the gap between scientific research and engineering practice...

- (6) After Alexander Klein, a research engineer at the University of California at Berkeley, had developed expansive cement over a six-year period, an industrial combine, holding the basic patent rights to products in the field of expansive cement, has been organized with the corporate name of Chemically Prestressed Concrete Corporation. This is enough evidence in their high hopes for its ultimate success. Comprising a cross section of inventors, producers, engineers, and contractors, this research, development, and promotional firm has its holding shares owned by Permanente Cement Co., Medusa Portland Cement Co., C. W. Blakeslee and Sons, Edward K. Rice, T. Y. Lin, Alexander Klein, and R. R. Pegram.

Besides licensing the patent rights to expansive cement to any domestic cement plant on a per-barrel royalty, the corporation is investigating its potential as a regularly marketable product and doing the promotional work. Though still a development product prior to general sale, mixtures of shrinkage-compensated cement and regular portland cement became available on the West Coast through Permanente in December 1963, and has become experimentally available in the Midwest, through Medusa. Another formulation of expanding cement and portland cement producing a concrete that prestresses itself by stretching high-tensile-strength steel may also be supplied upon order.

These proprietary materials are produced through basic modifications in the design of portland cement raw mixes. They have been produced in normal portland cement rotary kilns, and may be produced in quantities. The present (June 9, 1964) premium in California is \$1.40 per barrel over the delivered price of Type I cement. On an F.O.B. mill basis, the price is roughly \$4.80 per barrel in bulk and \$5.19 per barrel in bags, both subject to a 20¢ per barrel cash discount.

- (7) So far in this early developmental stage only two of its member companies, the Permanente and Medusa, of the Portland Cement Association are licensed producers of expansive cement. Its industry-wide interest as reflected by the work of the PCA Research and Development Laboratories may be seen from, but limited to, the paper, [32] released in 1963, of G. E. Monfore on their staff on the investigation of

mortar properties of expansive cement made with portland cement, gypsum, and calcium aluminate cement. These ingredients were not interground but simply blended just prior to the addition of fine aggregate and water--a way of adding expansive admixtures to the mortar mix.

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APPENDIX A: EXTRACTS FROM
AND DISCUSSION OF PAPER BY H. LAFUMA

1. Extracts from "Expansive Cements" by H. Lafuma^{8*} and the discussion thereof follow:

It will hardly be necessary to stress the disadvantages caused by the shrinkage of concrete in buildings; one of the more obvious results is the formation of cracks that will enable aggressive agents in the atmosphere or water to reach the interior of the concrete and the reinforcing steel. Shrinkage will also cause internal stresses inside the concrete and make it more brittle. And finally, it is an important disturbing element in the design of reinforced concrete structures.

Shrinkage is the property possessed by concrete of contracting on drying; it is closely related to the moisture content; the contraction increases when the concrete dries but will change to swelling when the concrete re-absorbs water. In other words, the apparent volume changes are reversible, at least approximately.

The study of shrinkage in concrete is extremely complex on account of the many factors that influence the phenomenon. It varies with the type of cement used, its fineness, the preparation of the mix, the amount of mixing water, the admixtures of soluble salts, the curing conditions etc. Only vague, or even contradictory data are available on the influence of the quality of the cement itself and, so far, it seems that the systematic investigations carried out in America have not been able to establish the influence of the various constituents, the results of various authors who have attempted to do so being in complete disagreement.

Therefore, the main effort has been directed towards reducing the amount of shrinkage by improving the manufacture and curing of the concrete. During the last few years, a great deal of attention has been paid to the possibility of counteracting shrinkage by the compensating action of certain factors—hence the idea of cements with compensated shrinkage—or even to transform the shrinkage into swelling, as suggested by Mesnager and later by Caquot and Lossier who pointed out the advantages that might ensue in improving the characteristics of the concrete.

To eliminate shrinkage entirely it would be desirable to produce a swelling equal to the shrinkage at any given moment, and this would mean that the swelling should take place during the drying period, which seems impossible. Consequently, it was necessary to adopt the following approximate method: swelling, exceeding the amount of shrinkage, is produced for a period of time lasting as long as possible, so that subsequent contraction on drying offsets the original swelling. The method applies to cement a phenomenon first taken advantage of in connexion with building plasters in which one of the constituents—anhydrous plaster—produces a certain amount of expansion that compensates the shrinkage of the hemi-hydrate.

Figure 1 gives a schematic representation of the principle.

* Raised numerals refer to similarly numbered items in Selected Bibliography at end of main text.

In practice, the compensation of shrinkage will require a cement producing a swelling of the order of 2 to 3 mm per metre; expansive cements have an initial swelling exceeding 7 mm per metre.

The materials that may be used as expansion agents are: lime, magnesia and calcium sulpho-aluminate. As Le Chatelier pointed out, the expansion is closely linked up with the hydration in the solid state without any previous solution: it is the result of the powdered condition of the hydrates formed, producing an apparent increase in volume that would prove detrimental to the mechanical strength of the concrete if it were left entirely free and unrestrained. Excessive expansion could result in complete disintegration of the concrete mass.

The necessity of obtaining a controllable expansion that will remain constant with time practically enforces the use of sulpho-aluminate as an expansion agent, but there is still the possibility of using it under various

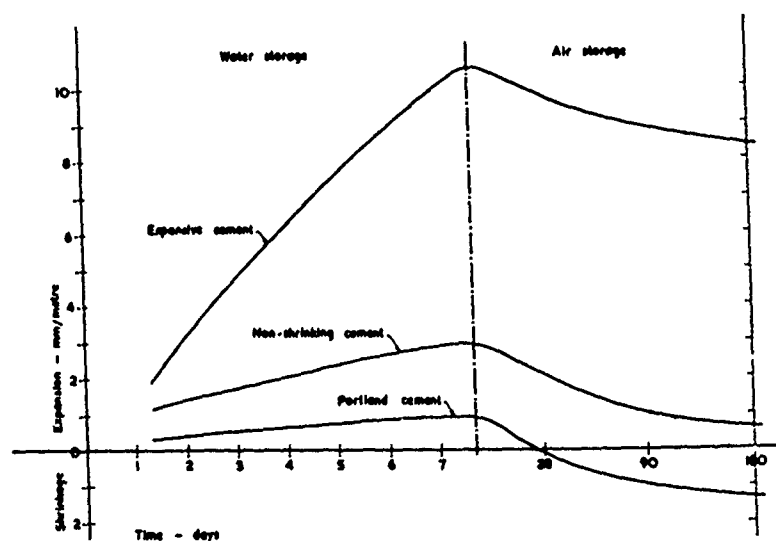


Figure 1.

forms since there is a certain latitude in the choice of the source and the amounts of alumina, calcium sulphate and lime required for its production. The idea and industrial adaptation have been effected by Hendrickx and his assistants.

The first expansion agent to give satisfactory practical results was a sulpho-aluminate clinker.

Starting from the idea that high temperatures might produce a combination of sulphate with lime and alumina, the technical experts of the firm "Poliet et Chausson" have tried simultaneous burning of gypsum, bauxite and calcium carbonate. The existence of a chloro-silicate $2\text{CaO} \cdot \text{SiO}_2 \cdot \text{CaCl}_2$, described by Le Chatelier, seemed to support the initial hypothesis of an anhydrous sulpho-aluminate.

After several laboratory tests, industrial production of the sulpho-aluminous cement was commenced, using a wet-fed rotary kiln. M. Perre, director of the Beaumont works describes the process as follows:

The mix is prepared by wet grinding of a mixture containing about 50 per cent gypsum, 25 per cent red bauxite and 25 per cent chalk, to a fineness of less than 3 per cent residue on the 900 sieve. The mix containing 42 to 45 per cent water is then burnt in a "Polysius Solo" kiln, with a length of 70 m and a diameter of 3.20 m, burning pulverized fuel. Burning takes place readily, clinker forms at an appreciably lower temperature than Portland cement. The material forms into conglomerates with a diameter of about 50 cm. These conglomerates break up automatically on entering the cooling chamber. Burning is carried out with a large quantity of excess air in order to reduce the amount of free SO_2 .

When the clinker has cooled, it is crushed and ground and this produces the sulpho-aluminous cement that will be mixed with Portland cement for the manufacture of non-shrinking and expansive cements.

The chemical composition of the sulpho-aluminous clinker may be as follows, for instance:

	<i>per cent</i>
Insoluble matter	2.8
Soluble SiO_2	7.0
Fe_2O_3	5.7
Al_2O_3	19.9
CaO	41.3
MgO	0.1
TiO_2	0.8
Loss on ignition	0.9
SO_3	22.1

It must be pointed out, however, that subsequent investigations on the clinker did not confirm in any way the original hypothesis regarding its composition.

X-ray analysis revealed the presence of important amounts of: free anhydrous calcium sulphate; calcium aluminate, particularly C_3A ; calcium silicate $\gamma\text{-C}_2\text{S}$.

Consequently, the clinker is probably composed of a mixture of the following substances: calcium sulphate 38 per cent; γ -dicalcium silicate 20 per cent; aluminates, ferrites and aluminoferrites 38 per cent; impurities 4 per cent.

X-ray examination does not reveal either ferrites or aluminoferrites, neither does it show up small amounts of impurities, and there is no "dusting" due to the presence of dicalcium silicate because the proportion of calcium sulphate will prevent it, according to the well-known observations of Candlot.

At this point, it might be useful to give a few brief considerations on sulpho-aluminous cements of this type. There is no reason why they should not be used. They are the only ones to produce remarkable strengths at early ages, comparable to those of aluminous cements. They have been studied and investigated on several occasions but have never been produced on an industrial scale. It would be possible to use either a mixture of high-alumina cement and calcium sulphate, or to burn a mixture of gypsum and bauxite, since the final product is a mixture of calcium sulphate and calcium aluminate. However, from this point of view, the clinker described above contains rather too much lime. The difficulty that prevented industrial

application, is the more or less unavoidable irregularity of the manufactured product, which is prohibitive in cement manufacture.

But, quite apart from these technical considerations, the clinker described above is being used for the manufacture of expansive cements, in a mixture with Portland cement of normal composition and of the best possible quality.

The fact that sulpho-aluminous clinker is a mixture of calcium sulphate, calcium aluminate and dicalcium silicate, and not a new sulpho-aluminate compound is sufficient proof that it is not absolutely necessary to use it but that there are other possibilities, such as a mixture of high-alumina cement and calcium sulphate, or of bauxite or pozzolana and calcium sulphate. But since the main factor is the rate of dissolution of these various substances, it may well be important whether the expansion agent is prepared by thermal treatment or by simple mechanical mixing.

But, to get back to expansive cements to be found on the market they are composed, in principle, of two cements; each cement is stable on its own: artificial Portland cement, which forms the basis and gives its own properties to the mixture; sulpho-aluminous cement, which constitutes the expansive agent.

A third, stabilizing, substance is added, i.e. blastfurnace slag, whose slow action enables the expansion to take place over a given period of time and which subsequently absorbs the excess calcium sulphate. An adequate choice of the grading and proportions of these three constituents will make it possible to control both the extent and the duration of the swelling. Figure 2 shows the action of slag in a cement causing a large amount of expansion.

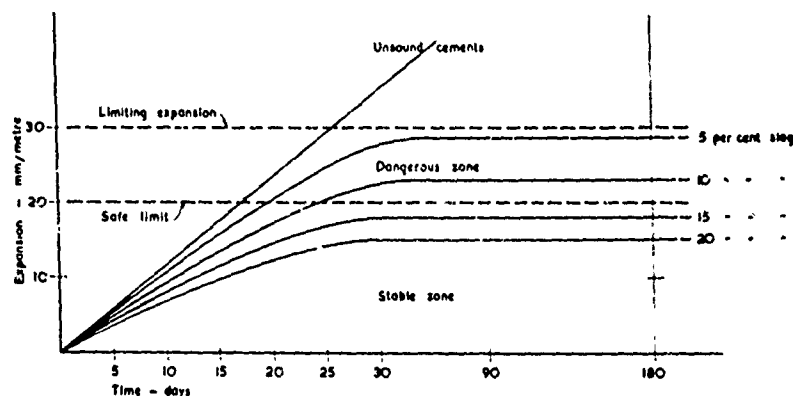


Figure 2.

Mixing should be carried out with the utmost care, since any irregularity will have a considerable influence on the results. The composition of non-shrinking cements is very similar to that of expansive cements, the only difference being that expansive cements contain larger amounts of sulpho-aluminous cement in order to produce the required expansion.

To avoid any subsequent damage, it is necessary that the expansion is

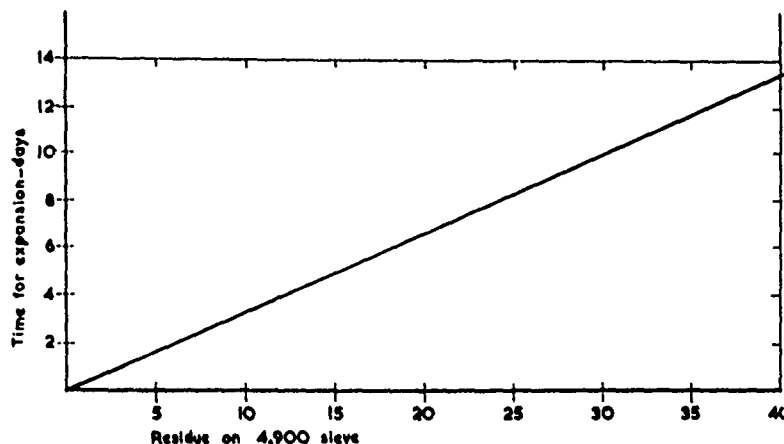


Figure 3.

completely under control as regards its extent and its duration. Premature expansion would lower the initial strengths. The expansion can be delayed by using rather a coarse grading for the sulpho-aluminous cement. It is useless to try to prolong the expansion beyond a period of about ten days on account of the difficulty involved in keeping the concrete sufficiently wet to enable the reactions to take place.

Figure 3 represents the duration of the swelling as a function of the fineness of the sulpho-aluminous cement.

It is quite easy to understand how the duration of the expansion is a function of the particle size of the sulpho-aluminous cement: finer particles will hydrate more rapidly. Moreover, finely ground cements will show less expansion, since the expansion represents the difference between the apparent initial and final volumes, and the finer the cement, the greater its apparent initial volume.

The amount of expansion can be controlled by the proportion of sulpho-aluminous cement added to the mix.

Expansion will start only when more than 8 per cent sulpho-aluminous cement is present.

The curve representing the swelling of expansive cement as a function of its SO_3 content is, of course, entirely similar.

Elongation starts only beyond 4 per cent of SO_3 . The Portland cement, has also a certain amount of influence. For similar SO_3 contents, the differences in elongation will be small but there may be an appreciable time lag on account of the strength of the Portland cement. The higher the strength, the slower the swelling because the two forces involved act in opposite directions; the expansion will be delayed in proportion to the strength of the Portland cement. The following table gives the mechanical characteristics

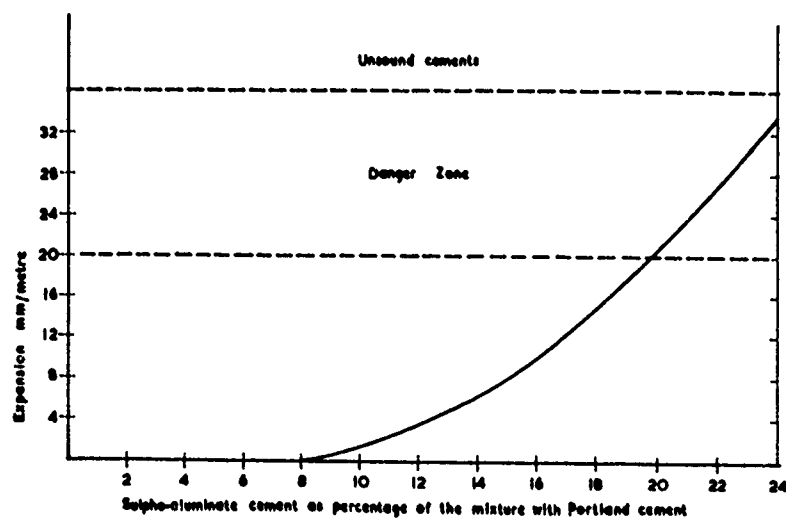


Figure 4.

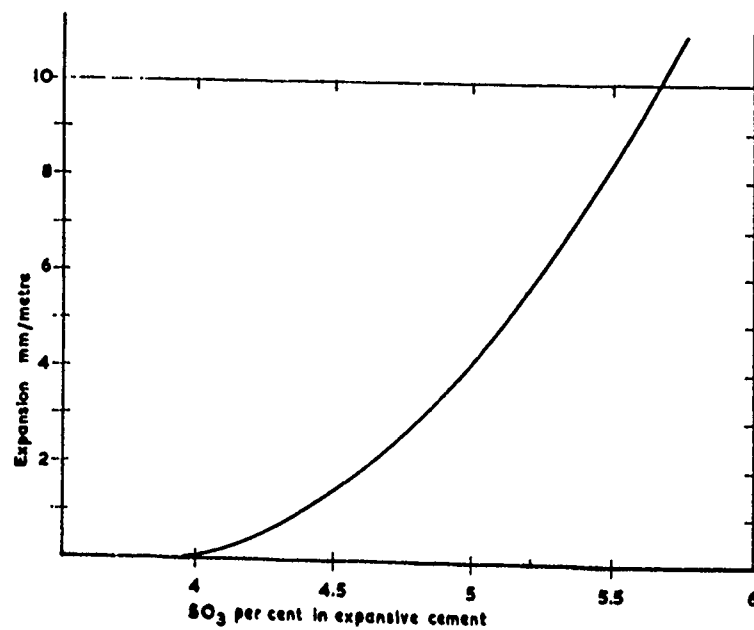


Figure 5.

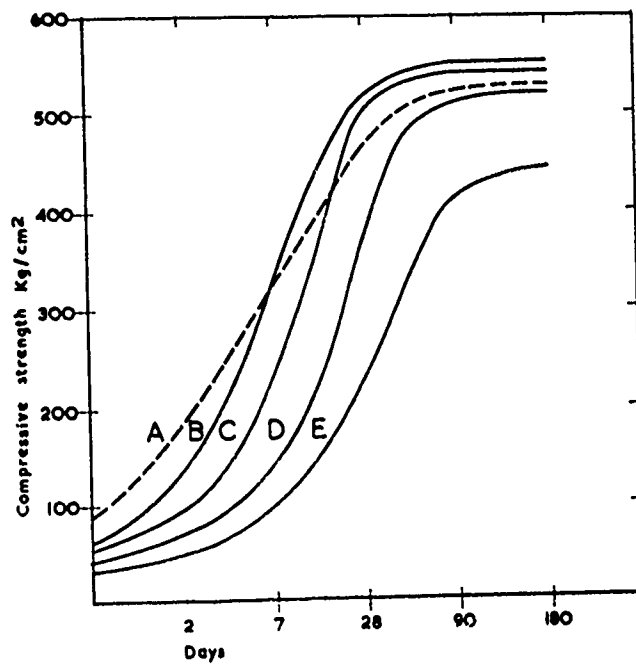


Figure 6.

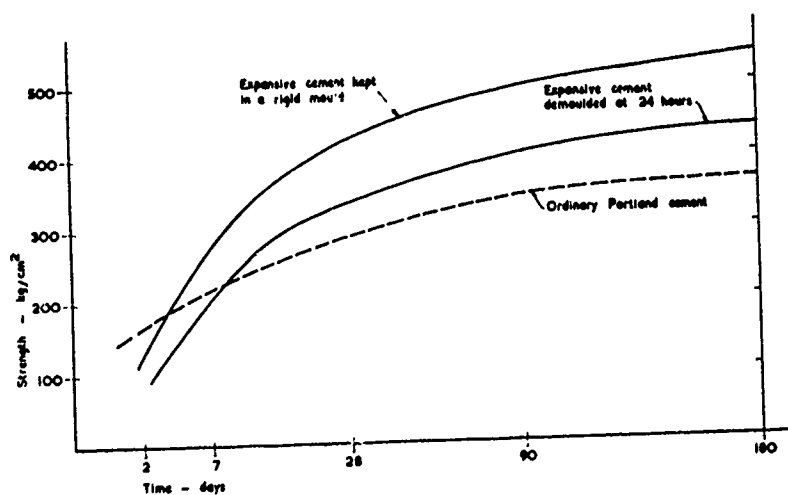


Figure 7.

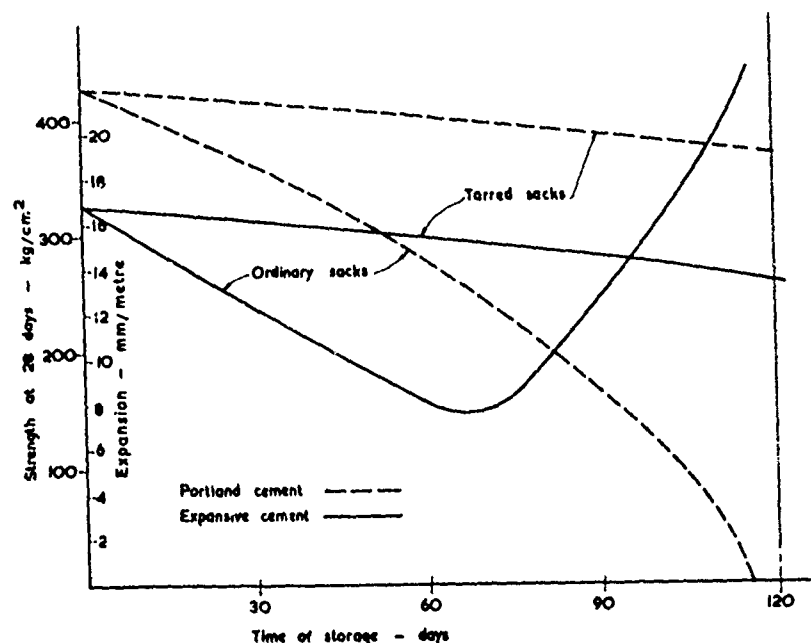


Figure 8.

of a few expansive cements in relation with Portland cement (Figure 6):

A	Portland cement								
B	Expansive cement SO, 4.4	per cent total swelling	2.75	mm per m.					
C	"	"	5.35	"	"	"	"	5.90	"
D	"	"	5.90	"	"	"	"	9.65	"
E	"	"	6.30	"	"	"	"	13.00	"

The test specimens used in this investigation were cured in water after demoulding. If the specimen is kept restrained in a mould during the curing process, a certain amount of self-stressing takes place and this increases the strengths to a considerable extent, as shown in Figure 7.

One of the advantages of expansive and non-shrinking cements is the improvement in water-tightness resulting from the absence of incipient cracking during the period of expansion. The cracks, started during the time when the concrete is still plastic, are the main cause of any subsequent permeability.

One disadvantage should also be mentioned; cements of this type aerate very easily. Figure 8 shows the strength and expansion values of an expansive cement kept for a certain amount of time in ordinary sacks or in sacks impregnated with tar.

To study the applications of expansive and non-shrinking cements would exceed the scope of the present paper. Lossier, who advocated their use in the first place, has described in the technical press a number of remarkable and spectacular applications—full references to these applications have been included in the bibliography. It will be sufficient to mention the following three points.

The first concerns the difficulties involved in the use of cements of this type. Since the expansion is, in fact, the difference between the initial and

the final apparent volume of the concrete, the expansion will be adequately defined only in so far as the compacting of the fresh concrete is itself adequately defined.

The second is relative to an important difference between expansive and non-shrinking cements. Contrary to what might be expected at first, it is easier to ensure a given amount of expansion than to compensate for the normal amount of shrinkage. This is due to the conditions of placing. When expansive cement is being used, the expansion is produced by systematic wetting of the concrete. Consequently, it will be sufficient to use a cement with a small excess swelling. Wetting of the concrete is stopped when the desired amount of expansion has almost been reached and, after a few hours, the swelling stops at the required limit. But the same technique could not be applied to non-shrinking cement and it is more difficult to control the wetting conditions and, consequently, to control the expansion.

The last point refers to the problems of large-scale industrial manufacture of specialized products of this type, although there is no doubt about their interest from the technical point of view. Cements of this type will necessarily find a very limited market and their manufacture will not have a very great commercial appeal. Commercial firms producing these cements do so without any great financial incentive and technicians should appreciate the fact that cement manufacturers have interested themselves in the solution of these problems.

2. Håkanson³³ in discussion of Lafuma's work⁸ noted that he had:

... followed the development of ciment expansif in France with a great deal of interest and I have read a good deal of the literature on it. In spite of this, there is one point that is not clear to me. I should like to ask what stresses are set up in the concrete and to what extent are they relieved?

We have made some simple experiments on beams $10 \times 10 \times 70$ cm and $20 \times 20 \times 70$ cm. We immersed them in water and fixed them into an apparatus, having demoulded them after two days. We controlled the length of the specimen and kept it constant by means of a screw. The stress was measured by means of a rather exact device underneath the beam and it was always found that at first the stress increased; later it decreased, sometimes practically to zero. Sometimes it remained at about 5 to 8 kg. per sq. cm. The maximum varied between 15 and 27 kg. per sq. cm., and was reached within a week, the stress decreasing soon after. It appears to me that in concrete which is fairly well restrained, this cement acts in the following way. At first it expands and sets up a stress but owing to the plastic flow that stress is more or less relieved and after the first two weeks when there is no appreciable stress to counteract the shrinkage it appears to me that this concrete will shrink and crack just like ordinary concrete.

2
3. Lafuma replied that:

... the expansive force has been measured in numerous experiments in France and is found to be about 30 to 40 kg. per sq. cm., becoming stabilized by creep at about three-quarters of its maximum value. Concrete made from expansive cement if dried out undergoes a shrinkage of the same order as normal concrete, measured with reference to the dimensions attained at the moment of beginning the drying cycle.

4. Meyer³⁴ in the discussion of Lafuma's work⁸ asked for Lafuma's view:

... on the possibility of using expansive cements for concrete roads, keeping them constantly under compression and thus avoiding joints. A British engineer has proved that the weight of the concrete slab is sufficient to ensure that there will be no blow-up. According to the very interesting experiments mentioned by Mr. Hakanson,^[33] think the possibility is not very great. Professor Lafuma mentioned in his paper that if the expanding concrete is restrained in its form an increase in strength takes place on account of the extra compression. I should like to know how the concrete acts when it is released; in other words, how much of the unrestricted expansion is regained and how much is converted into creep? I know that some investigations have been made but I should like to have this point elucidated.

5. Lafuma replied:

It is not possible to give a definite answer to Dr. Meyer's query. Limited trials on road sections in expansive concrete suggest that it is possible to increase the spacing of the joints. If the concrete is restrained during the period of rapid expansion, the expansion produced on releasing the restraint is only that to be expected having regard to the restraining force and the elasticity of the concrete. But restriction of the expansion will affect the mechanical properties of the concrete.

Notable authors, such as Lossier, have subscribed to the view that expansive cement can be used to bring about self-stressing, but I do not personally believe this, for the following reasons.

The expansion of the cement is due to the formation of calcium sulphoaluminate under particular conditions, the mechanism resembling that involved in the slaking of quicklime. I shall discuss the latter reaction, which is the simpler. The absolute volumes involved in the reaction $\text{CaO} + \text{H}_2\text{O} = \text{Ca(OH)}_2$ are 1 c.c. + 1 c.c. = 1.8 c.c. As is general in hydration reactions, there is an overall diminution in absolute volume. An apparent expansion results because the calcium oxide becomes hydrated without first dissolving in the water. The reaction takes place in the solid state, and since 1.5 c.c. of hydrate is formed from every 1 c.c. of oxide, there is necessarily an expansion accompanied by pulverization and disruption of the solid mass.

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In the case of expansive cement, the expansion is due to the formation of sulpho-aluminate, but because of the cohesion produced by the other constituents, there is no disruption; the cohesion naturally diminishes if the cement is not restrained.

The stress developed by the hydration of lime is restricted, as Le Chatelier has shown, for the following reason. The solubility of hydrated lime is increased by pressure. It follows that in a moist mass of hydroxide subjected to pressure, recrystallization takes place relieving the stresses; there is always space for this because of the absolute decrease in total volume accompanying hydration.

The same limitation applies in the case of calcium sulpho-aluminate, and that is the reason why in my opinion it is not possible to achieve such high tensions in the steel as are obtained mechanically in prestressed concrete.

6. Cowan³⁵ in the discussion of Lafuma's work⁸ asked for his views:

... on the results of tests on expansive cement concrete recently carried out in the civil engineering department of the University of Sheffield.

It seemed reasonable to assume, and indeed it had been suggested by various writers, that the expansion of the cement, if resisted by suitable steel reinforcement, could be utilized to produce initial compressive stresses in the concrete similar to those which would be induced by mechanical prestressing. Two barrels of expansive cement manufactured by Poliet et Chausson, Paris, were procured and two beams were cast together with the appropriate subsidiary test specimens. A 1:2:2 concrete mix was used with a water-cement ratio of 0.5. The dimensions of the beams were 6 in. by 9 in. by 8 ft 6 in. long. Each beam was reinforced with four half-inch diameter high tensile steel bars with an ultimate strength of 150,000 lb. per sq. in., one bar in each corner of the rectangular cross-section. The beams were fitted with thick steel end-plates. The bars passed through these end-plates and were threaded at the ends and fitted with nuts bearing against the end-plates. These nuts were made finger tight only. It was assumed that the expansion of the cement, duly observed in our subsidiary tests, would induce tensile stresses in the steel and corresponding compressive stresses in the concrete.

One of the beams was tested in pure bending, and the other in pure torsion. The results were compared with experiments on four Portland cement concrete beams, of which two were normally reinforced and the other two mechanically prestressed. I may add that the torsion test is extremely sensitive to small increments in initial compressive prestresses.^[36] We found that the strength of the expansive cement beams was only slightly higher than that of the normally reinforced Portland cement beams, and well below that of the mechanically prestressed beam.

We thought that this negative result might be explained by the apparently very low cohesive strengths of the expansive cement at the time when most of the expansion takes place. If the expansion is resisted in one direction, the volume flow of the concrete would then produce expansion mainly in some other direction. In the case under discussion the expansion parallel

to the axis was resisted by the steel reinforcement while the expansion across the beam was opposed by the steel mould. The concrete, could however, expand without obstruction in an upward direction.

If this is the correct explanation of our test results it would limit severely the possible applications of expansive cement for the purpose of prestressing, since it could only be used in confined positions. All the successful applications of expansive cement of which I am aware are, in fact, of this type^[37] I should be very glad to have Professor Lafuma's views on this point and I would also be grateful for any further information on the mechanics of the expansion process.

7. Lafuma replied that:

In the particular experiment quoted by Dr. Cowan it may be that expansion took place vertically, but even if this were not so, the results would be explained by what I have already said.

The formation of ettringite (sulpho-aluminate) is also controlled by the temperature, anomalies appearing at 30 to 40°C as shown by Kühl and confirmed by Brocard and myself. The experiments of Dr. Gille are as far as I know the only ones of their kind.

8. Gille³⁸ in the discussion of Lafuma's work⁸ noted that:

In his excellent paper on expansive cements Professor Lafuma had shown the difficulties that their use on a large-scale basis involves. In our investigations we found that besides other influences temperature also affects the expansion, expansion going up with the decreasing temperature. There was a remarkable difference even between the behaviour at temperatures about 19°C and 32°C, as shown at the right of Figure 1, that is, in the temperature range in which concrete is usually laid. It is presumed that these differences depend upon altered conditions for the formation of ettringite.

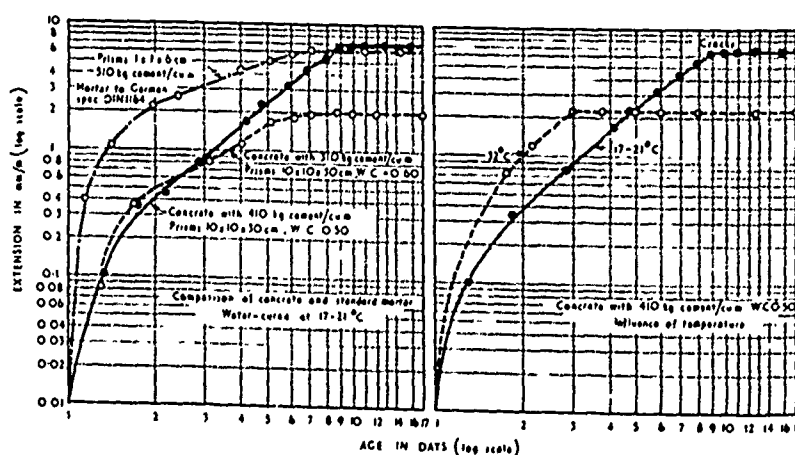


Figure 1: Change in length of mortar and concrete specimens with time, when made with expansive cement.

9. Andrews³⁹ in discussion of Lafuma's work⁸ noted that Lafuma had:

... mentioned in his paper the expansion of gypsum plasters and I should like to make one or two comments on this aspect even though it is somewhat outside the main theme of this symposium. It is well known that mixes of plaster of Paris and water expand on setting to gypsum, though consideration of the density of the phases involved shows that there is a reduction in true volume. The expansion is caused by the arrangement of the gypsum crystals which, in growing, create pores in the set material. The set product, still containing a considerable proportion of water, shrinks on drying, a characteristic of most porous materials. The unrestrained expansion is normally many times greater than the shrinkage. It becomes less as the proportion of mixing water increases and can be significantly affected by other materials present or added. Its magnitude may vary between zero and 0.5 per cent linear or even higher. Tests at the Building Research Station have shown that the shrinkage on drying from saturation to equilibrium in air of 65 per cent relative humidity is also dependent on the proportion of water used for mixing, becoming less as the proportion is increased. It may vary between 0.01 and 0.02 per cent and increases if the humidity of the air is reduced.

The setting expansion of plaster of Paris, even if it is fairly high, is normally no disadvantage. Indeed, for producing plaster casts it constitutes one of the most useful characteristics of the material as it enables the finest details of the moulding to be accurately reproduced. In some instances, however, its expansion may give rise to difficulties and defects. In building the use of plaster with a high setting expansion may cause distortion of building boards to which it is applied or may affect adhesion to smooth surfaces such as some types of concrete. In dentistry and in some engineering work it can lead to undesirable dimensional inaccuracies. Methods are known and used for controlling the setting expansion of materials based on plaster of Paris. In dentistry and other work, plasters with a very low expansion and a convenient setting time are obtained by the use of potassium sulphate and borax. In building plasters a mixture of a keratin-type retarder and a small proportion of lime gives a satisfactorily low expansion. Such additions are considered to effect a reduction in expansion chiefly by modifying the crystal habit of the gypsum formed on setting, but a disadvantage of the use of lime is that it carbonates during storage and eventually becomes ineffective. Portland cement has the same effect as lime in reducing the magnitude of the setting expansion, and has the advantage of a slower rate of deterioration through carbonation during storage.

10. Goria and Appiano⁴⁰ in discussion of Lafuma's work⁸ noted that:

In his paper Professor Lafuma concludes his description of the chemical, physical and mechanical performances of Lossier's cement by mentioning three particular points.

The first concerns the difficulty when using these cements, of defining the amount of expansion (that is the difference between the initial and the final apparent volume of the concrete).

The second essentially points out the difficulty of controlling the wetting conditions and consequently the expansion.

The third refers to the problems of production on an industrial scale.

For the third point we remark that in agreement with the experiences of other authors [13,14,15] the simplest way to manufacture these expansive cements is by merely grinding a mixture, thus avoiding the unnecessary heating of the sulpho-aluminous expansive component.

APPENDIX B: EXTRACTS FROM AND DISCUSSION OF PAPER BY
BY V. V. MIKHAILOV

1. Extracts from "Stressing Cement and the Mechanism of Self-stressing Concrete Regulation" by V. V. Mikhailov^{21†} and the discussion thereof follow:

During setting and hardening, cement components are hydrated and acquire new structural forms, accompanied by concrete volume change.

At these changes, the internal stresses in the colloid particles, and between them, appear and are either partially or completely localized. Hence cement paste and concrete undergo uninterrupted volume changes.

Cement paste expansion, in consequence of so-called "inconstant volume," or of the influence of sulfate water, causes cracking, just as concrete shrinkage, highly undesirable, also leads to cracking.

Fargoing research has long been engaged in efforts to eliminate the harmful influence of shrinkage on reinforced concrete, or to provide conditions to obtain setting and hardening without shrinkage. Only in 1942 was this problem basically solved, ... [by the development of waterproof, expansive cement called WEC].

WEC is obtained by combined dry grinding of high-alumina cement, gypsum, and artificial C_4AH_{13} (known as the mineral hydrocalumite). The latter is obtained by joint hydration of high-alumina cement and lime, followed by drying and grinding. The degree of expansion of this cement is largely regulated by change in the proportions of components.

Formation of calcium hydrosulfoaluminate $C_3A(\bar{CS})_3H_{32}^*$ (ettringite), known as "cement bacillus," concrete's most dangerous enemy^[41] and the cause of considerable concrete building damage, is employed to solve this problem in cement expansion not only for shrinkage elimination but also to obtain some expansion. Calcium hydrosulfoaluminate appears in the early stages of WEC hydration and its formation is completed shortly after cement setting. Expansion thus begins and also ends in the short time of the cement paste stiffening, i.e., during the early period and first phase of cement

* The symbol \bar{S} is here used for SO_3 . The bar distinguishes from $S = SiO_2$

† Raised numerals refer to similarly numbered items in Selected Bibliography at end of main text.

hardening, thereby completely avoiding the harmful influence of ettringite formation.

It was in 1943 that WEC cement first came into use to rebuild war-destroyed reinforced concrete constructions; later in subway construction to replace lead for caulking joints of cast iron tubings, guaranteeing watertightness, high strength, and quick building. WEC cement finds use also in coal pit bracing. Good results were also obtained by expansion cement application in the repair and restoration of underground infiltrated concrete constructions.

To date we have worked out very simple and rapid methods of tamping cracks, holes, and cavities, which immediately stop water filtration, making the construction ready for use.

It is customary to apply waterproof cover as a concrete jacket in underground construction, when shotcreting with WEC concrete greatly simplifies the work.

An isolation layer of a WEC concrete, 3.5 cm thick, can be placed directly on the damp surface, promptly stopping water seepage. Such layers are applied to isolate dam surfaces, hydrostation tunnels and pipes, buttresses, tanks, and other underground and sea constructions. The method is applicable in building repair to restore to proper condition damp or submerged premises.

Thus, ... waterproof expansion cement ... has overcome the difficulties involved in concrete contraction. Again, this cement is used in various branches of construction to replace lead, metal, and other materials. Creation of this cement is an example of the profitable use of harmful factors in construction building, "cement bacillus" for example, whose formation and structural expansion are connected with the initial period of WEC existence, when the colloidal formation in cement paste is maximum.

All known cements are now applied only to make strong stone from ballast, gravel, and sand, but these binders have unexplored qualities far beyond present applications.

Cement's "inconstant volume" and the possibilities of regulating nonelastic expansion are as yet not profitably employed. These factors establish a condition in concrete in which the reinforcement becomes extended and prestressed, making unnecessary the mechanical methods now practiced. This novel idea of creating self-stressing, obtainable by the help of stressing cement, opens wide horizons for application in building, and provides economy in materials and expenditure.

... stressing cement ... is a tricomponent binder made from finely ground portland cement, high-alumina cement, and gypsum, taken in optimum proportions. Mixed with a low amount of water, this cement sets and hardens quickly. Cured by hardening under the required hydrothermic conditions, stressing cement acquires sufficient strength and expands, carrying the reinforcement along and thereby creating self-stressed construction. High mechanical strength, watertightness, and prestressing possibilities make stressing cement a valuable binder for prestressed construction, assuring both watertightness and high tension resistance.

Any portland cement (in amounts of 60-70 percent) to which high-alumina cement and gypsum have been added in the proper proportions makes self-stressed cement.

2. Mikhailov²¹ reviewed his concept of the mechanism of setting and hardening of portland cement as a basis for developing an explanation of these mechanisms in expansive cements. He stated that:

In considering the structure of high strength portland cement clinker we distinguish two structural varieties of clinker compound compositions.

(1) portland cement of high alumina content (fig. 1), in which polymineral structures C_3S and C_2S are glued with a glasslike mass of calcium aluminate (C_3A) and some calcium ferroaluminate (C_4AF).

(2) brownmillerite portland cement (fig. 2) in which polymineral structures C_3S and C_2S are glued with a glasslike mass of calcium ferroaluminate (C_4AF) exclusively. Here C_3A is absent.

To stabilize the technical properties and to regulate setting time, the portland cement clinkers are ground with a small amount of gypsum, which can react quickly with the alumina compounds of the clinker in water medium.

Any mixture of portland cement with water, as a result of absorption and chemical dispersion of the cement grains, which are splinters from the mechanical grinding of clinker compounds (fig. 3), disintegrates into separate micro and colloidal particles clearly described by P. A. Rehbinder.^[42] Such a dissociation is accelerated by high solubility of alumina and ferroalumina glasslike matrix compounds and outwedging water action (Rehbinder), owing to penetration into numerous microcracks of cement splinters. As a result, active surfaces of cement grains quickly increase and hydration and hydrolysis are accelerated. Special investigations (A. Smirnov) with the application of radioactive isotopes have shown that 1 hr after mixing of C_3A with water (fig. 4), the active surfaces of cement increase from 3,000 to 300,000 cm^2/g , or by a hundred times. The

explanation of these dissociations is that in chemical and mechanical processes cement particles less than 10μ disintegrate fully into particles of colloidal size (0.1 to 0.01μ), and form colloidal cement glue. Larger cement splinters of polymineral structure C_3S and C_2S , cannot fully dissociate even over a long time and always retain kernels of cement splinters, untouched by water. The cement glue layer, when the quantity of colloidal formation increases by new colloidal particle absorption, gives a saturated solution, and hydrated crystallization occurs directly around the remaining cement kernels, separated from the former by water diffusion layers, free of soluble salts. In the process of further dissolving, new hydrated ions and molecules of clinker salts are continuously ejected through this layer and are concentrated in the area of colloidal structure of hardened cement paste and are absorbed by the nearest crystalline hydrated formation. The hardened cement paste forms structures where the former cement, new formation, free water, and air are reacting.^[43] The role of the latter is also important because hydration speed and volume change, which continuously accompany the structural changes, largely depend on the air distribution in the structure. A schematic drawing (fig 5) shows the hardened cement paste structure, conditionally, after the alumina compound formations are fully hydrated, which requires little time. By this time, C_3S , and to a small degree C_2S kernels, decrease by hydration from the surface. As the hydration process of C_3S kernels develops, the water diffusion layer diminishes and the process slows down and finally stops because of water



FIGURE 1. High alumina portland cement structure, rich in C_3A and C_4AF .



FIGURE 2. High alumina portland cement structure, C_3A -free.



FIGURE 3. Polymineral structure of portland cement grains
Published by Prof. A. A. Raikov
Enlargement 350 times

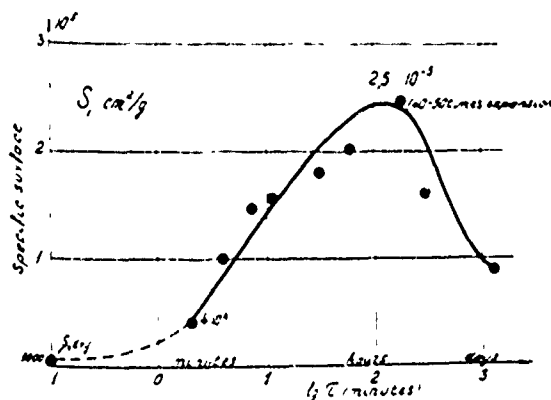


FIGURE 4. Diagram of cement grain active-surface increase during first hydration period

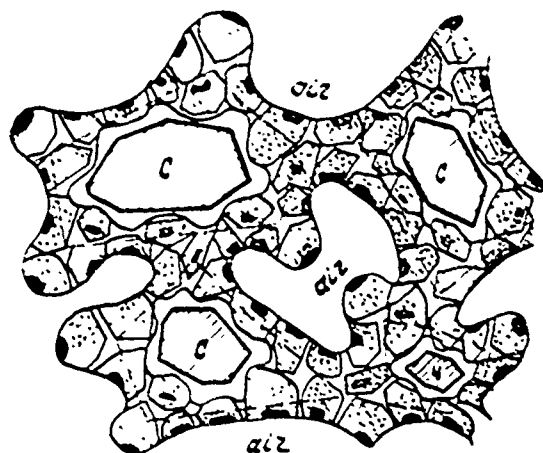


FIGURE 5. Scheme of gel and air distribution in hardening cement paste

deficiency. The more air bubbles, large and small, spread through the structure, the quicker is the development of solution saturation and new crystallization. N. V. Mikhailov [44] has shown in his research on cement hydration the existence of two stages of structure formation:

(a) the stage of formation with predominance of thixotropic coagulation structure, with reversible recovery after mechanical destruction, and

(b) the stage of strengthening, characterized by both crystallization and coagulation structure.

These two stages are definitely distinguished by

the change of plastic properties of the cement paste, and are established by continuous and regular tests with a plasto-viscosimeter (method of N. Mikhailov and E. Kalmikova) [44]. For every kind of cement paste there exists one distinctive point (fig. 6) when the plastic strength of structure increases quickly.

In the coagulation structure, soon after its formation, the processes of calcium hydroaluminate crystallization proceed quickly with unusual formation of crystalline needles and chains, which

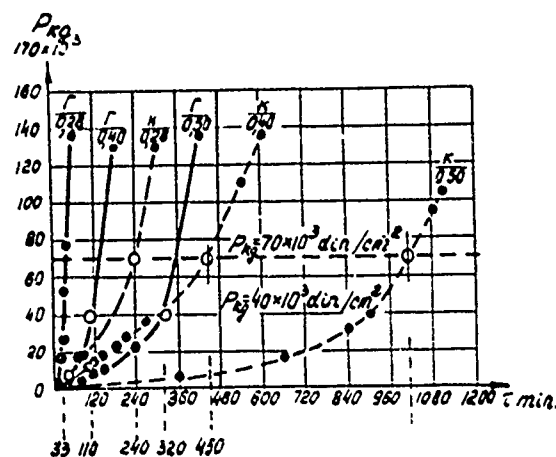


FIGURE 6. Changes of cement paste plastic strength with time, for different cements and different water contents.

pierce the coagulation structure of the slow hardening hydrosilicate components like a framework. After the cement paste colloidal phase reaches maximum saturation of new formations, these structures are thickened and completely form such a pseudo-crystalline framework.

Maximum saturation is characterized by a breaking point in the diagram (fig. 6), which exactly divides the different states of cement paste structure.

By cement setting and hardening, ions of hydrated clinker salt are ejected to the more distant solution zone, free of hydrated salt influence. Movement of these ions becomes more difficult, the more bubbles, big and small, in this solution (fig. 5). During the first stage, ions of calcium, alumina, and ferroalumina clinker salts predominate, to which later calcium silicate ions are added. Very soon, particularly with low water content in the mixture (hard paste consistency), oversaturation of solution is attained and crystallization begins, giving compounds of new formation, glue-like in appearance, and different in form and configuration. Then the process of crystallization accelerates, following partial water release, with absorption on the new formation surfaces.

As a result of permanent water exhaustion in the direction of nonhydrated clinker kernels, the new formations, in crystallization and coagulation states, are in permanent compression. Particles of these formations draw together (fig. 7), because of molecular attraction in the zones of capillary particle contacts.

Surface capillary tension in these contacts also draws the particles closer. The equilibrium now depends on the capillary forces which attract the structural particles and simultaneously push the particles away. Later these forces not only act spontaneously but also through the thin layer of the water jacket covering the particles.

Water molecules which have lost their mobility

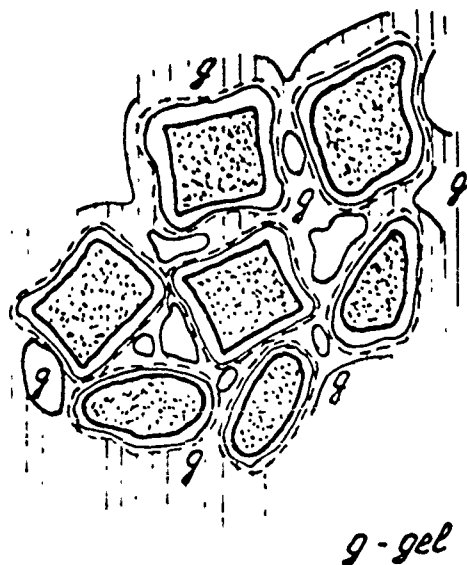


FIGURE 7. Scheme of hardening cement structure.

and are attached to particles by attraction forces due to the tensioning influence between the particles are gradually squeezed out from the contact and packed densely, often replacing by direct molecular interaction new hydrated particle formations. As a result chains, needles, rods, and friable splines of colloidal new particle formations appear and unite or connect by molecular cohesive forces. During C_3S and C_2S hydration, water exhaustion of their kernels causes difficulties, thins the free water layer and finally stops the clinker salt hydration long before expending all the salt reserves. To a certain extent, external water feeding can prolong hydration, but not for a long time. The central zones of C_3S kernels, and especially C_2S , remain as a permanent clinker salt compound, as has been described by Yoong.^[45]

If the cement paste structure had no air bubbles, each cell between cement grains (generally three) would be filled with water and with hydrated ions of clinker salts, forming only one dimension of crystal, which could freely move in this cell because there is nothing to prevent free transfer in the stream of thermal molecular movement.

If the cement paste cells are air filled (fig. 5), ions may be ejected to the boundary "cement glue-air", and, as a result, along the whole boundary of this cell the possibility exists of forming a great number of crystalline centers, and, in this area, very dense and dispersed cement paste structures arise. These consist of a ramified network of hydrated alumina and ferroalumina compounds, filled (to overflow) with hydrosilica structures. Some scientists^[46] affirm that with the hydrosilica formation a crystal of large dimension cannot grow when water content is low, with which we absolutely agree. But this refers only to hardening at temperatures below 100 °C.

When the temperature is over 100 °C, and particularly above 140 °C, even in mixtures with very low water content, calcium hydrosilicate crystallizes in a fibrous network of long lathlike and rodlike crystals known as a tobermorite formation,[47] which explains the high mechanical strength of the cement paste in question.

The Soviet method of concrete vibropressing[48,49] followed by hermetic concrete curing at 140-150 °C in the pressed state, aims to attain strong tobermorite structure quickly. It has already been pointed out that in the state of structure formation, cement glue consists chiefly of alumina and ferroalumina hydrated clinker compounds, which form sufficiently developed fibrous splines and framework.

This structure itself cannot play any important role in cement paste strengthening, but can to a considerable extent insure uniform distribution of hydrated silicate in the whole volume of cement

glue, preventing large particles from growing, and providing future high strength of cement paste.

Future cement paste strength can be further increased by repeatedly destroying these cement paste formations by mechanical influences, for example, vibration. In this case there is demolition of many fibrous framework ties which are immediately restored, but in dense structure. During this restoration calcium hydrosilicate crystallization takes place, giving very dispersed and strong cement paste structure. It was on this principle that methods of vibromixing, vibropunching, vibropressing, etc., were developed.

When the alumina and ferroalumina crystalline hydrated formations predominate in cement paste structure, it is possible by varying the amount of water, and by mechanical coercion, vibration and thermal curing to build and rebuild cement paste structure to attain maximum strength.

3. Since one of the two types of expansive cement described by Mikhailov^[1] is used principally for its watertightness, he described the phenomenon of watertightness as follows:

During the setting and hardening of many known cements, the volume of materials decreases, because of more dense placing of hydrated clinker salts than cement grains plus free water.

Therefore the primary cement paste volume $(C+W+A)$ decreases its volume by hydration to

$$[C+W+A-(1-K)(C_h+W_h)] \quad (1)$$

where C_h =the original volume of the amount of cement that reacted, W_h =water volume for this hydration, A =air volume, K =ratio of the specific volume of the hydrated product to the original specific volume of the mixture of cement and water that reacted.

Equation (1) shows that by hydration the concrete volume undergoes chemical shrinkage, since $K < 1$. There is also physical shrinkage by loss of free water, W , in dry air. Chemical shrinkage is large, and it appears chiefly in volume change during setting and during the first hours of cement hardening. For example, the high-alumina cement paste shrinkage in 1 day is 0.7 percent of primary length, and for portland cement paste 1 percent. Shrinkage is also large if cement paste is water-hardened, causing difficulty during hole and cement joint tamping. Later, by dry storage, physical shrinkage develops as cement paste dries. In wet storage, swelling appears and the volume of cement paste increases.

When the liquid phase of hardened cement paste is in equilibrium with air moisture, no volume change in cement paste occurs.

The interaction between the colloidal formations of cement paste is regulated by cohesive forces of capillary contact (fig. 8). The theory of capillary contact, worked out in 1941,[43] shows that this interaction is determined by free water surface curvature in capillary contacts between new cement paste formations and is described as

$$r_1 = \sqrt[3]{\frac{3V}{4\pi\alpha} \left(1 + \sqrt{1 - \frac{\pi x^3}{3\alpha^2 V}}\right) - \frac{x^3}{8\alpha^2}} + \sqrt[3]{\frac{3V}{4\pi\alpha} \left(1 - \sqrt{1 - \frac{\pi x^3}{3\alpha^2 V}}\right) - \frac{x^3}{8\alpha^2} + \frac{x}{2\alpha}} \quad (2)$$

and the interaction forces as

$$K = \frac{\pi\gamma r_1}{4 r^2} \left(\frac{1}{\frac{\alpha}{2} + \frac{x}{2r_1}} - 1 \right) \quad (3)$$

where V =water volume in contact, α =inclination angle of sharp contact side, x =distance between firmly attached colloidal particles, without taking into account water layers, r_1 =working diameter of capillary contact, r =average particle dimension, to determine the number of particle contacts in unit surface, γ =surface tension of water.

The cement paste system, under these interaction forces, is always in a state of external compression, constantly changing value when the surrounding air humidity changes. The change of this compression in structure causes cement paste volume changes and shrinkage.

Shrinkage can be calculated by eq (4):

$$\lambda_{sh} = \frac{\pi}{4r^2 E_c} \left[\frac{3}{2} \frac{\gamma^2}{1,300 \ln \frac{1}{\phi}} - 3\gamma \sqrt{\left(\frac{3}{2} \frac{\gamma}{1,300 \ln \frac{1}{\phi}} \right)^2 + r \left(\frac{2\gamma}{1,300 \ln \frac{1}{\phi}} \right)} + r \left(2\gamma - x \frac{1}{1,300 \ln \frac{1}{\phi}} \right) \right] + \Delta x \quad (4)$$

where ϕ =relative humidity of the air.

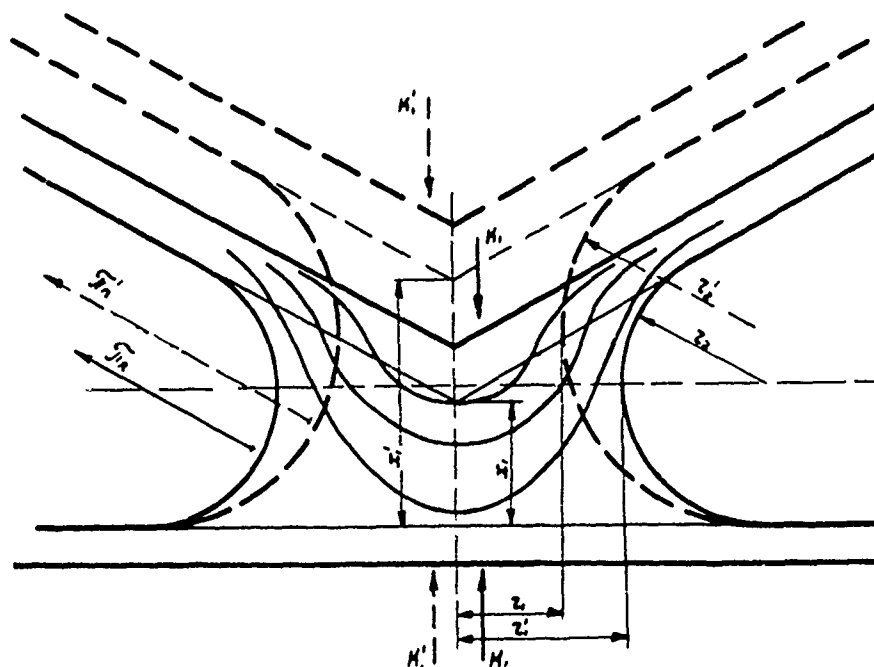


FIGURE 8. Scheme of coherence of colloidal particles in capillary contact of cement paste.

Insofar as water exhaustion into diffusion layers and new particle formations and compression by capillary forces develop continuously, in similar manner the average water surface curvature in capillary contacts [43,50] continuously changes. If at any early moment the humidity of the surrounding air and the water content of the cement paste were in equilibrium, at the next moment, by increasing the humidity, equilibrium disappears and water condensation begins, which relieves the particles' capillary compression, lowering shrinkage. If unlimited humid flow of air is maintained, there is full compensation of shrinkage compression. When hardened cement samples are stored in water, its unlimited ingress produces concrete swelling; but in this case interparticle pores and spaces filled with water increase. If these samples are placed in dry air, cement paste quickly loses water from the large pores, and gives higher shrinkage than in the normal hardening condition. On the other hand, in dry air from the first moment of cement setting and during hardening, equilibrium is absent, and cement paste loses water the more rapidly the larger the pores of the cement structure. As a result high shrinkage appears, connected with water decrease in the capillary contacts. With very dry air and large pores, water loss is so rapid that cement hardening may completely stop. This water loss is accompanied by a high shrinkage (physical factor). The importance of sufficient water retention, especially during the time of setting and first period of hardening, is clear.

TABLE 1. Technical code for waterproof expansion cement—WEC

No.	Qualities	Measurement data
1	Stable volume changes.....	By water setting and warm testing, no volume change.
2	Setting time: (a) Initial set, not before..... (b) Final set, not later than.....	4 min. 10 min.
3	Grinding fineness: (a) Residue on screen No. 200, not more than..... (b) Passed through screen No. 90, not less than.....	12 percent 75 percent.
4	Compression strength, not less than: (a) Cubes 20 x 20 x 20 mm made with cement paste of normal plasticity, water-stored 1 hr after mixing: Age: 2 hr..... 6 hr..... 3 days..... 28 days..... (b) Prisms 31.5 x 31.5 x 100 mm, made with mortar of normal plasticity, 1:2 (by weight), stored 1 hr after mixing: Age: 24 hr..... 3 months.....	75 kg/cm ² . 300 kg/cm ² . 500 kg/cm ² . 120 kg/cm ² . 200 kg/cm ² .
5	Elongation of 31.5 x 31.5 x 100 mm prisms made with cement paste of normal plasticity: (a) Dry-air-stored and tested at age of 1 day, not less than..... (b) In water after 1 hour and tested at age 1 day, not less than..... 28 days, not more than.....	0.05 percent. 0.2 percent. 1.0 percent.

Cement paste in normal storage after long water storage gives greater shrinkage than cement paste with initial curing in air.

Cements are applied in structures as mortar or concrete. The external effect of shrinkage is less than in pure cement, because of aggregate resistance. But the degree of cement paste shrinkage in the cells between aggregates is the same; there-

fore in the cement paste structure high tensile stresses arise, which can result in microcracks. Microcracks permit water seepage which penetrates through the concrete, not only by applied pressure, but easily because of its own weight. The consequences of cement shrinkage are seen in cases of cement repair of filtrated cracks and holes when the cement paste cracks, or the cracks appear on the hole edge. Invisible microcracks can easily be seen when filtration begins at once upon application of water pressure.

4. Mikhailov²¹ described the conditions of formation and the stability, structure, and manner of crystalization of the calcium aluminum sulfate ($C_3A(C\bar{S})H_{12}$) as follows:

Former investigations of calcium silicate and aluminate products of cement hydration have analyzed new cement paste structure formations. But such research gives a picture only of the hydrated system with high water content.

Furthermore, the newest technique of concrete production uses less water in concrete, with the result that the structure formation develops differently.

We can affirm that cement hydration with low water content gives quite new formations hitherto unknown. In this connection, we also worked out new methods that influence structure formation. Finally we were able to externally affect structure-building processes and deliberately conduct and change them.

This rebuilding presents large-scale possibilities, still untouched, to obtain new cement paste structure forms.

Broad research by famous scientists in the direction of studying cement paste structure and the mechanisms of their formation and growth, by petrographic microscope, electron diffraction, and electron microscope give no results. This is because these methods cannot test and study the processes of hydration of cement with low water content.

At times this confuses the researcher since the conditions do not correspond to reality.

Difficulties increase because the influence of cement paste structure formation is operative not only at the time of setting, in the first minutes and hours of cement hardening, but at any other time when the original cement paste structure is sufficiently formed and strengthened.

Defects of all microscope methods of cement paste structure analysis result from the manner of sample preparation with high water content, when the required structure form does not appear, or of sample preparation by paste grinding, rubbing, and surface polishing of hardened cement paste, when the structure studied completely disappears or basically changes. Therefore for microscopic analysis we applied special microphotographic methods with very thin nondisturbed cement paste samples which were hydrated on glass (method of Yoong^[45]). The feature of this method is in fine

WEC application provides full shrinkage compensation and sufficient expansion. WEC technical properties are given in table 1.[51]

Lab testing of WEC must be done in definite sequence, differing considerably from the ordinary cement testing. It must be remembered that WEC storage and transportation is permitted only in hermetic packing. WEC technical data must be controlled monthly.

cement grinding, with hydration on a glass plate with a low quantity of water, placing on the glass in a very thin layer and pressing with the glass cover to spread the paste. Some samples are then hermetically isolated by glue or paraffin. Thus we obtain nondisturbed cement paste samples, which are stored in dry air, humid air, and water.

It must be said that this method, though only qualitative, answers the questions: Has the structure the formations we are looking for? When do they appear or disappear? Positive advantages of this method of analysis are the possibility of prolonged and continuous optical study of all changes which occur in structure formation, and the possibility of protecting hydrated compounds from carbonation (by CO_2 in air).

Studies by Danelian on high-alumina cements with various compositions gave the following average chemical content:

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Loss on ignition
12.3	44.3	4.5	35.0	1.4	1.9	0.60

This cement consists chiefly of CA and low quantities of C_2S and C_2AS . Immediately after mixing it gives a hexagonal structure rich in crystalline water— C_6AH_{34} , with index of refraction 1.487–1.480.

Table 2 gives structural formations and strength of high-alumina cement paste hydrated at 0.3–0.4 water cement ratio, and stored in dry air, humid air, and water.

Hexagonal formations of C_6AH_{34} and C_2AH_8 appear in dry storage, but are unstable and soon disappear, recrystallizing into forms of the low-calcium CAH_{10} . The strength does not increase with time, and remains at a low level, about 250–300 kg/cm².

Hexagonal forms C_6AH_{34} and C_2AH_8 which are more stable appear in humid and water storage. Here cement paste strength reaches 950 kg/cm² at the age of 1 yr.

Specimens hardening in water give a similar picture. Here new forms with 1.480–1.495 light

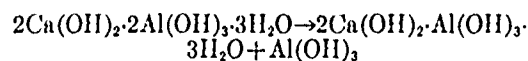
TABLE 2.—High-alumina cement

Cement paste properties	Storage condition	Age, days						
		3	14	28	90	180	270	360
New hydrated cement formation.	Air.....	C_3AH_6	C_3AH_6	C_3AH_6	C_3AH_6 C_4AH_{13}	C_3AH_6 C_4AH_{13}	.....	1.47
	Humid air....	C_3AH_6	C_3AH_6	C_3AH_6	C_3AH_6 C_4AH_{13}	C_3AH_6 C_4AH_{13}	C_3AH_6 C_4AH_{13}	.....
	Water.....	C_3AH_6	1.519-1.534	C_3AH_6 C_4AH_{13} C_4AH_{13}	C_3AH_6 C_4AH_{13} C_4AH_{13}	C_3AH_6 1.480-1.498 C_4AH_{13}	C_3AH_6 1.477-1.493	1.46
Compression strength, kg/cm ²	Air.....	256	.....	372	370	321	.....	.....
	Humid air....	640	.....	810	.....	951	.....	.....
	Water.....	761	.....	941	966	943	.....	.....

refraction, which can be attributed to C_3AH_6 , are visible. This structure differs from those of the new formations brought about by alumina cement hydration in suspension, when the products of hydration are C_3AH_6 , C_4AH_{13} , and C_3AH_6 , depending on lime content.

The hexagonal forms C_3AH_6 and C_4AH_{13} were very definite in investigations of water storage samples. These structures can be described as alternations of hydroxyl layers: C_3AH_6 —as $2Ca(OH)_2 \cdot 2Al(OH)_3 \cdot 3H_2O$; C_4AH_{13} —as $2Ca(OH)_2 \cdot Al(OH)_3 \cdot 3H_2O$.

All hexagonal calcium hydroaluminates, as is known from the literature, have a family likeness in electron diffraction. C_3AH_6 has a tendency after a time to dissociate into C_4AH_{13} and $Al(OH)_3$ by the reaction:

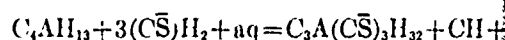


but the layer structure does not break, only one layer of $Al(OH)_3$ attains the amorphous state.

Hydroaluminate attains high lime content formation, C_4AH_{13} in the main, when the lime con-

tent is high, which results from alumina cement hydrated together with lime.

All hexagonal calcium hydroaluminate formations become unstable and recrystallize in cubic form, C_3AH_6 . Hexagonal formation hydration at high temperature has never been seen when gypsum is absent. It is different when cement is hydrated together with gypsum. In this case hexagonal forms are quite stable at normal and high temperature. Gypsum immediately reacts with C_4AH_{13} :



By insuring contact with water the formation of $C_3A(C\bar{S})_3H_{32}$ quickly ends. It appears in form of lathlike rods at low lime concentration and in form of thinnest needles at high lime concentration. Gypsum binding in $C_3A(C\bar{S})_3H_{32}$ accelerated by adding C_4AH_{13} .

Table 3 gives the structure formation, strength data and volume changes of WNC cement pastes samples hydrated at 0.3-0.4 water-cement ratio and stored in dry air, humid air, and water.

TABLE 3. Tricomponent waterproof cement WNC

Alumina cement—75 percent by weight
Gypsum ($CaSO_4 \cdot 0.5H_2O$)—6.25 percent by weight
Artificial hydrocalumite C_4AH_{13} —18.75 percent by weight

Cement paste properties	Storage condition	Age, days						
		3	14	28	90	180	270	360
New hydrated formation.	Air.....	C_3AH_6	C_3AH_6	C_3AH_6	C_3AH_6 C_4AH_{13} AH_3	1.489-1.504 1.498-1.504	.....	1.498-1.504
	Humid air....	C_3AH_6	C_3AH_6	C_3AH_6	C_3AH_6	C_3AH_6	C_3AH_6 C_4AH_{13}	.....
	Water.....	$C_3A(C\bar{S})_3H_{32}$	$C_3A(C\bar{S})_3H_{32}$	$C_3A(C\bar{S})_3H_{32}$	$C_3A(C\bar{S})_3H_{32}$	.....	$C_3A(C\bar{S})_3H_{32}$	.....
	Water.....	1.510-1.528 C_3AH_6	1.522-1.537 1.486-1.195	1.519-1.528 C_3AH_6	C_3AH_6 $C_3A(C\bar{S})_3H_{32}$	C_3AH_6 $C_3A(C\bar{S})_3H_{32}$	C_3AH_6 $C_3A(C\bar{S})_3H_{32}$	.....
Compressive strength kg/cm ²	Air.....	207	.....	200	202	235	.....	.....
	Humid air....	210	.....	343	340	377	.....	.....
	Water.....	210	.....	275	380	430	.....	.....
Elongation(+) or shrink- (-) %	Air.....	-0.08	-0.16	-0.18	-0.22	-0.22	-0.47	-0.47
	Humid air....	-0.05	+0.02	+0.12	.....	+0.49	+0.40	.....
	Water.....	+0.08	+0.09	+0.15	+0.33	+0.40	+0.31	.....

Cement WNC is a variety of WEC, but with lower gypsum and higher C_4AH_{13} content. It gives little expansion in humid storage and is called waterproof nonshrinking cement.

This cement is characterized by quick setting, quick hardening, and instantaneous watertightness.

Due to this property, WNC is applied for caulking strongly filtrated cracks, holes, cavities, etc.

Table 3 shows that WNC, after mixing, gives hexagonal formations C_2AH_8 and $C_3A(CS)_2H_{12}$ at once. On the third day of hardening, the high-lime formation C_4AH_{13} does not appear, because of the latter's quick reaction with CS with formation of $C_3A(CS)_2H_{12}$, showing light refraction of 1.464-1.458, but only in the case of humid and water storage. In dry storage no traces of $C_3A(CS)_2H_{12}$ are found. In long storage (over 360 days) crystals of gypsum were continuously present.

WNC strength is low (a characteristic of this cement). It is 50 percent of normal high-alumina cement strength in humid storage, and only 25 percent in dry storage. But despite this, WNC is indispensable when there is destruction to repair.

The process changes basically by adding lime to high-alumina cement instead of artificial hydrocalumite C_4AH_{13} , when gypsum is present. C_2AH_8 and C_4AH_{13} formations then appear, react with gypsum, and form calcium sulfoaluminate, now as a "low sulfate" structure— $C_3A(CS)H_{12}$ with light refraction 1.489-1.504 and chain-connected hex-

agonal plates. When lime is present and the water content limited, at first hydration results only in the "low sulfate" structure, formerly unknown. But this formation is unstable, and with gypsum present and high water content, recrystallizes into the "high sulfate" structure of calcium sulfoaluminate— $C_3A(CS)_2H_{12}$ —with intensive expansion.

$C_3A(CS)H_{12}$ has plate structure, similar to hexagonal calcium hydroaluminate, and its formation does not lead to expansion.

Table 4 gives new structure forms and light refraction, specimen strength, and volume change for high-alumina cement, gypsum, and lime hydrated together in the proportions 88:4:8 at 0.3-0.4 water content, and stored in dry air, humid air, and water.

At 3 days C_2AH_8 and $C_3A(CS)H_{12}$ are found in all samples, as well as at 14 days. Later, $C_3A(CS)H_{12}$ disappears in air-stored samples, but C_2AH_8 , C_4AH_{13} and gypsum are present. Test specimens show shrinkage which reaches 0.44 percent at 270 days. C_2AH_8 and $C_3A(CS)H_{12}$, in humid air and water-stored samples were stable at 3 days, but at 28 days, the water-stored samples showed the high sulfate structure of calcium sulfoaluminate, and expansion was 0.73 percent, causing cracking. Gypsum crystals were also very plainly seen. At 180 days "low sulfate" structures disappear because of complete recrystallization into the "high sulfate" form. Expansion reaches 2.47 percent, cracks open wide, and gypsum disappears completely. Because of large expansion, specimen strength is low, and after 1 yr of water storage is 176 kg/cm².

TABLE 4. Tricomponent waterproof cement

Alumina cement—88 percent by weight
Gypsum ($CaSO_4 \cdot 0.5H_2O$)—4 percent by weight
Lime (CaO)—8 percent by weight

Cement paste properties	Storage condition	Age, days						
		3	14	28	90	180	270	360
New hydrated cement formation.	Air.....	1.519-1.528 1.480-1.498 C_4AH_{13}	C_2AH_8 C_4AH_{13} $C_3A(CS)H_{12}$	1.480-1.498 1.507-1.528 C_2AH_8	1.480-1.498 1.507-1.528 C_2AH_8	1.480-1.498 C_2AH_8 $C_3A(CS)H_{12}$		1.488-1.471
	Humid air ...	C_2AH_8 $C_3A(CS)H_{12}$	C_2AH_8 $C_3A(CS)H_{12}$	C_2AH_8 $C_3A(CS)H_{12}$	C_2AH_8 $C_3A(CS)H_{12}$	C_2AH_8 $C_3A(CS)H_{12}$	C_2AH_8 $C_3A(CS)H_{12}$	C_2AH_8 $C_3A(CS)H_{12}$
	Water.....	C_2AH_8 $C_3A(CS)H_{12}$	C_2AH_8 $C_3A(CS)H_{12}$	C_2AH_8 $C_3A(CS)H_{12}$	C_2AH_8 $C_3A(CS)H_{12}$	C_2AH_8 $C_3A(CS)H_{12}$	C_2AH_8 $C_3A(CS)H_{12}$	
Compressive strength kg/cm ² .	Air.....	191		277	290	313		304
	Humid air...	172		216	220	150		167
	Water.....	182		247	248	179		178
Elongation (+) or shrinkage (-)	Air.....	-0.08	-0.07	-0.12	-0.24	-0.30	-0.44	-0.31
	Humid air...	+0.01	+0.08	+0.23	+0.73	+2.30	+2.45	+2.60
	Water.....	+0.06	+0.15	+0.26	+0.70	+2.11	+2.47	+2.63

5. Stressing cement, designated "SC," by Mikhailov,²¹ was described

by him as follows:

The use of gypsum was for a time highly recommended as an additive for portland cement to attain rapid hardening and strength increase.

Naturally, this composition did not achieve good results, as the formation of $C_3A(CS)H_{12}$ and the

following slow recrystallization into $C_3A(CS)_2H_{12}$ led to a drop in strength and sometimes to concrete destruction. This feature was intensively studied in Germany by the Dyckerhoff firm,^[52] manufacturers of special brownmillerite sulfate-

resistant cement which does not increase the concrete volume and is not destroyed when gypsum is added. It differs in this respect from normal cement with a large tricalcium aluminate content, which together with a low water content gives the "low-sulfate" form of sulfoaluminate of calcium, with subsequent destructive recrystallization into the "high-sulfate" form. Considering in this connection two examples of portland cements (see figs. 1 and 2), attention should be paid to the fact that sufficient iron oxide in the cement to a high degree retards the formation of dangerous forms of calcium sulfoaluminate, even in calcium hydroxide saturated media. Complete absence of C_3A is a characteristic feature of this brownmillerite cement, which is why it is not destroyed in sulfate water.

In other countries, scientific thought seeks to counteract the destructive influence of sulfate water by introducing pozzolan into the concrete during mixing. D'Ans and Eick^[53] and Eitel^[54] have shown that adding pozzolan does not eliminate the formation of calcium hydrosulfoaluminate. It only retarded ettringite formation for weeks and months.

The formation of the "low-sulfate" form of calcium hydrosulfoaluminate proceeds violently, and subsequent recrystallization into the "high-sulfate" form occurs in mechanical mixtures of portland cement, high alumina cement (or other aluminate compounds) and gypsum powders. Thus, a paste mixture of 65 percent portland cement, 15 percent gypsum, and 20 percent alumina cement of normal consistency, stored in water after hardening 2-3 days to a strength of 200-300 kg/cm², rapidly expands, due to the water absorption and "high-

sulfate" formation, until it is finally disintegrated into an adhesive finely dispersed mass. This mixture has no hydraulic properties and would appear to be unfit for use. Yet its expansive power is very great. As explained in detail below, such a hardening cement mixture, not immersed in water, does not cause hydrosulfoaluminate recrystallization.

The cement paste in this case expands somewhat on account of the mix water, but is not destroyed. However, if such a cement paste is immersed in water even after 1-2 yr, the recrystallization process is renewed with great force and the system is completely destroyed, forming an adhesive mass.

It is clear that this type of cement cannot ever be used for construction purposes.

Investigating the hardening processes of portland cement clinker mixed with gypsum in various proportions, we noted that, even for small additions of gypsum reacting with C_3A , the formation and recrystallization of calcium hydrosulfoaluminate took some time, longer when water ingress into the system became more difficult.

It is possible to make up the initial combination of components with low water content so that upon isolated storage of the cement paste (without water admission) the expansion stops at a definite age. However, when water is admitted the process is renewed and leads to expansion, which finally stops without destroying the system.

As an example, cement paste of the proportions 14:20:66 (gypsum, high-alumina cement, portland cement) mixed with 30 percent water (fig. 9) may be used. Along the abscissa, days are plotted and, along the ordinate, relative expansion

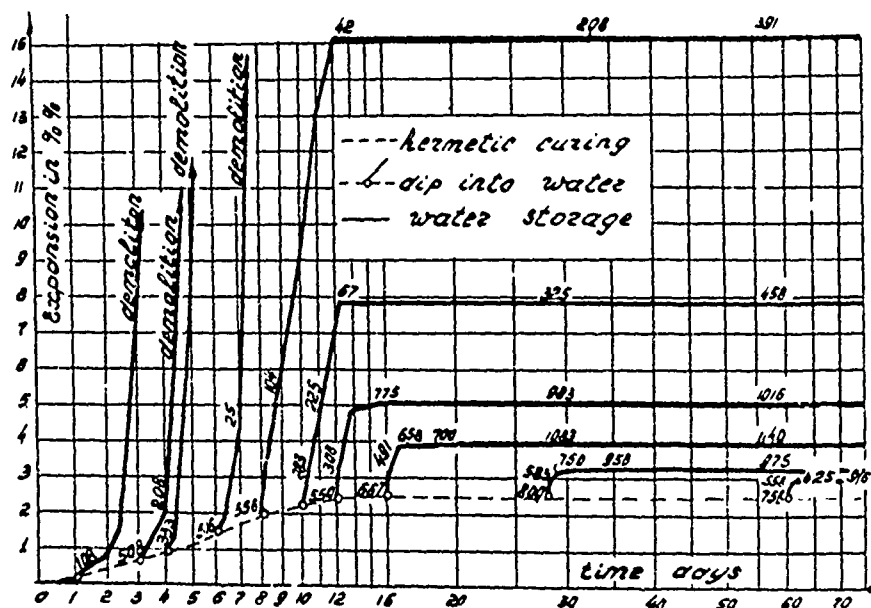


FIGURE 9. Expansion-strength diagram of stressing cement paste at 200 °C in the isolated state showing changes with time at which immersed.

of the sample in percentage. The dotted line shows expansion of sample during isolated storage in paraffin-coated foil. At 15 days, expansion is stabilized at a level of $2\frac{1}{2}$ percent. Cement paste strength at this age equals 667 kg/cm^2 ; after 28 days 800 kg/cm^2 . If such samples are taken from isolation on 1, 3, 4, and 6 days and immersed in water, they expand rapidly and samples are completely disintegrated. Samples immersed after 8 days and having at that time a strength of 558 kg/cm^2 showed rapid recrystallization to "high-sulfate" formation, but were not destroyed completely and retained their shape without any signs of cracks. At 12 days, i.e., after 4 days of water storage, the samples had expanded 15 percent (fig. 10) and the strength was only 42 kg/cm^2 . However, during further water storage, at 28 days the strength reached 208 kg/cm^2 , and at 60 days, 391 kg/cm^2 . Samples immersed after 10 days, with strength of 560 kg/cm^2 , had expanded 8 percent at $12\frac{1}{2}$ days, and the strength had dropped to 67 kg/cm^2 , but with further water storage a strength of 458 kg/cm^2 was attained at 60 days.

For samples immersed after 12 days, the strength, which was then 536 kg/cm^2 , dropped temporarily to 308 kg/cm^2 at 13 days, but at 15 days rose to 775 kg/cm^2 . The expansion was 5 percent, and the strength continuously increased, reaching $1,016 \text{ kg/cm}^2$ at 60 days.

Similar results were obtained when samples were immersed after 15, 28, and 60 days.

The curve in question shows that, with increase in specimen age at the time when immersion begins, additional recrystallization of the calcium hydrosulfoaluminate occurs by additional water absorption, but in a lower degree and in less destructive form. However, all specimens during the initial water expansion period showed a temporary 30-35 percent drop of strength.

The example mentioned shows that the processes of setting, hardening, and expansion of the tri-component composition of portland cement, high-alumina cement, and gypsum may be controlled. Later we will show that it is possible to direct these processes by optimum proportioning of components. Henceforth this composition will be called stressing cement SC (see table 5--Technical Code). [55]

Self-stressed cement paste is composed of selected cement paste structure with prearrangement and reorganization of the entire structure during cement, mortar, and concrete setting and hardening processes. Previously, examples of directed interference with cement paste existence and behavior were unknown.

Pure portland cement and high-alumina cement are best applied as clinker, first grinding them for SC preparation. It is advisable that the cement fineness be not less than $3,500 \text{ cm}^2/\text{g}$. The tri-component powders are batched in the vibrating mill for 8-10 min, to uniformity.

At low water mixture (25-30 percent by weight), lime, portland cement, and the CA of the alumina



FIGURE 10. View of SC hydrated specimen with 15 percent elongation, immersed 8 days after isolated storage (see figure 9), in comparison with similar portland cement (nonelongated) specimen.

cement dissolve rapidly and a large amount of water is absorbed. Ions of hydrated minerals rush toward the zones of lower concentration of the liquid phase and crystallize, and meeting with gypsum grains they react and form lathlike splines of calcium hydrosulfoaluminate on gypsum grain surfaces.

The plastic strength of the system rapidly increases, beginning 2-3 min after mixing.

The saturation with calcium hydrate, and the limited water phase, hampers the growth of the "high-sulfate" formation $\text{C}_3\text{A}(\text{CS})_3\text{H}_{32}$ which is limited by formation of a "low-sulfate" product $\text{C}_3\text{A}(\text{CS})\text{H}_{12}$.

As a result, a branched framework is formed of $\text{C}_3\text{A}(\text{CS})\text{H}_{12}$, C_4AH_{13} , and $\text{C}_3\text{A}(\text{CS})_3\text{H}_{32}$ lathlike splines.

The last two needlelike formations are completely intertwined. The higher the water cement ratio at hydration, the more $\text{C}_3\text{A}(\text{CS})_3\text{H}_{32}$ and the less $\text{C}_3\text{A}(\text{CS})\text{H}_{12}$ and pure gypsum.

This intertwining is, during the initial period, rather loose gradually becoming compacted by

TABLE 5. Technical code for stressing cement (SC)

(Specifications)		
No.	Qualities	Measurement data
1	Setting time: (a) Initial set, not before..... (b) Final set, not before.....	2 min 6 min
2	Fineness of grinding: (a) Residue on screen, N 02, not over..... (b) Passing through screen N 0225, not less than.....	1 percent 90 percent
3	Strength of cubes, size 20 x 20 x 20 mm, made of cement paste of normal consistency, should be as follows: (a) For specimens cast 18-20 hr at 20±2 °C, not less than..... (b) For specimens cast 18-20 hr at 20±2 °C and then 6 hr (without molds) in water at 70° C, not less than..... (c) For specimens given hydrothermic treatment in conformance with § "b" of the given item and then stored in water at 15-20 °C for 24 hr: Not less than..... Not less than.....	200 kg/cm ² 450 kg/cm ² 600 kg/cm ² 850 kg/cm ²
4	Elongation of prism, size 31.5 x 31.5 x 100 mm, made of cement paste of normal consistency, given hydrothermic treatment according to the sequence described in § "b", should be at the end of treatment not less than..... Elongation of prism during such treatment, in relation to the elongation value at the end of 6-hr thermal treatment, should be: (a) After 2 hr thermal treatment, in the range..... (b) After 3 hr thermal treatment, in the range..... Increase of specimen elongation in water storage, in relation to the elongation value at the end of thermal treatment, should be: After 7 days, not over..... After 28 days, not over..... NOTE. Conformance with requirement of §§ "a" and "b", item 3, and §§ "a" and "b", item 4, is rapid test of SC	2-2 percent 75-85 percent 92-97 percent 12 percent 15 percent
5	Strength of cubes, size 30 x 30 x 30 mm, made of normal consistency SC mortar (1:1) by weight, should be: (a) For specimens cast 18-20 hours in molds at 20±2 °C, not less than..... (b) For specimens cast 18-20 hours at 20±2 °C and then 6 hours (without molds) in water at 70 °C, not less than..... (c) For specimens given hydrothermic treatment in conformance with § "b" of given item and then stored in water at 20±2 °C: After 1 day, not less than..... After 3 days, not less than..... After 7 days, not less than..... After 28 days, not less than.....	150 kg/cm ² 250 kg/cm ² 300 kg/cm ² 300 kg/cm ² 200 kg/cm ² 500 kg/cm ²
6	Elongation of prism, size 31.5 x 31.5 x 100 mm, of normal consistency SC mortar (1:1) by weight, should be: At end of thermal treatment (according to § "b" item 5), not less than..... During further water storage 15-20 °C: After 1 day, not less than..... After 3 days, not less than..... After 7 days, not less than.....	2 percent 0 percent 1.5 percent 1.8 percent
7	Samples of cement paste of normal consistency mortar (1:1) by weight, during testing (in disks) at the end of thermal treatment should be entirely impermeable at pressure.....	20 atm

ions and newly formed silicate compounds, which crystallize in the aluminate and sulfonaluminate framework. A feature of crystalline calcium hydrosilicate formation is that, in media with a small amount of water, development rapidly stops, and the growth does not exceed the limits of colloidal dimensions. There is strong competition between all reacting new formations in the cement paste colloidal zone, which quickly leads to exhaustion of moisture resources and retardation of the hydration of the initial cement materials. After about 24 hr of isolated natural hardening (to prevent carbonation of new forma-

tions) the strength of the cement paste reaches 200-300 kg/cm², and the cement paste coagulation-crystallization structure is characterized by the presence of a highly branched framework of intertwining heavy splines of lath, needle, and lattice-like formations of hydrosulfonaluminate structure and chains of calcium hydroaluminate. The space taken up by these compounds is filled with a coagulation structure of hydrated silicate formations, disintegrated nonhydrated cement kernels, and gypsum grains coated with a solid feltlike shell of C₃A(CS)H₁₂.

SC cement, in a high-water-content mixture, forms C₃A(CS)₃H₃₂ quickly and without interference, because the indefinite number of hydrated ions of CA of high alumina cement and the quantity of C₃A and C₄AF in the portland cement gradually delivered, rapidly react with the gypsum under conditions of relatively low Ca ion concentration. But the reaction of C₃A(CS)₃H₃₂ formation rapidly ends during the early hardening period when the strength of cement paste is low. In this case there is no noticeable expansion of the system.

Thus, SC with low water mixture supplies the best condition for obtaining in the system the maximum quantity of C₃A(CS)H₁₂, ready for recrystallization.

If such a hardened system is immersed, the cement paste greedily absorbs water and the recrystallization process rapidly converts C₃A(CS)H₁₂ into C₃A(CS)₃H₃₂, with simultaneous expansion of the system, for the process occurs on gypsum grain surfaces, and causes structural rearrangement with water absorption. The C₃A(CS)₃H₃₂ structure is formed on the gypsum grain surface like directed thin needles and presses against the adjacent new formations, disturbing their adhesion. As a result of this growth, the structure is completely demolished and breaks into separate small pieces. This behavior was observed in cement paste specimens (fig. 9), immersed in water after 1, 3, 4, and 6 days of isolated storage. Simultaneously, due to CS₂ recrystallization of C₄AH₁₃ formation into C₃A(CS)₃H₃₂ occurs.

If expansion of the system during recrystallization is limited to 15 percent, total destruction does not occur, but as mentioned above, destruction of mechanical adhesion between colloidal particles of C₂SH₂ and CSH leads to structural weakening, which, after expansion stops, heals as the result of delivery of ions of hydrated silicates of calcium and the development of new connections. For specimens immersed after 15 days, healing proceeds very quickly, and some weakening is observed only in brief loss of strength.

Destruction of structural adhesion as a result of recrystallization to C₃A(CS)₃H₃₂, and the formation of new connections, may also be directed by shifting the destruction and restoration periods, timing them to the accumulation of new high strength silicate formations, and superimposing them for strength stabilization.

Hydrothermic treatment of the system is effective for such formerly discussed adjustment.

Through heating, the influence of the hydration of the silicate cement components is highly accelerated. Therefore the reproducing processes are performed rapidly and at a certain temperature do not lag behind the processes of structure destruction. During a definite time, as many and even more connections are restored as are destroyed. Because of this, the strength is either maintained at the fixed level, or even increases on expansion.

Heating of the system makes it possible not only to avoid excessive expansion and destruction of the cement paste, but also permits time decrease for all processes, which, according to the curve (fig. 9), take so long to develop.

Investigations have shown that heating cement paste for 2 hr at 70-80 °C when the strength is about 200-300 kg/cm² gives expansion sufficient for the system without any signs of strength drop.

Figure 11 shows data on expansion and strength increase of SC specimens heated at 80 °C for 1, 2, 3, 5, and 7 hr when the initial strength was 200 kg/cm². All samples heated 2, 3, 5, and 7 hr expanded 2 percent and reached strength of about 500 kg/cm². Further water storage of SC samples did not show more expansion, because the gypsum was fully consumed during the first 2 hr of heating, and all $C_3A(CS)H_{12}$ was recrystallized into $C_3A(CS)_3H_{32}$.

However, the strength of the cement paste continuously increased owing to the progress of the hydration of the C_3S and C_2S of the portland cement, leading the system to further densification. Cement paste after 28 days reaches a strength of 1,200-1,300 kg/cm². Thus, heating the system for

more than 2 hr had no effect in any case. It might be assumed that such hydrothermic treatment during hardening would be selected as best for application in structures; however, with mortar, difficulties were met with. The composition of SC paste, which resulted in an increase of strength accompanying 6 percent expansion during heating, showed a much greater strength drop in mortar, sometimes 2-3 times, making this composition of mortar unfit for self-stressing.

Actually, reinforced concrete self-stressing is possible only when the concrete bond with reinforcement exists and concrete acts as a hard body, deforming identically and simultaneously with the steel. For such reinforcement action, concrete should continuously possess the required strength and density. Insufficient strength due to temporary drop causes plastic concrete flow around the reinforcement, without its significant lengthening. Thus, we obtain large reinforced concrete expansion, but without self-stressing, even though, during further hardening in water storage, the strength is not only restored, but significantly exceeded. This may be because, during the rapid process of SC expansion, cracks arise from the retarding action of the aggregates, which do not increase in volume.

All attempts to prevent the drop in SC mortar strength lead to lower expansion power, and in turn to insufficient self-stressing.

Self-stressing technology has therefore been greatly changed.

Investigations showed that $C_3A(CS)H_{12}$ recrystallization into $C_3A(CS)_3H_{32}$, in calcium hydrate media, is retarded by further temperature increase; simultaneously, hydration of C_3S and C_2S is considerably accelerated at the higher tem-

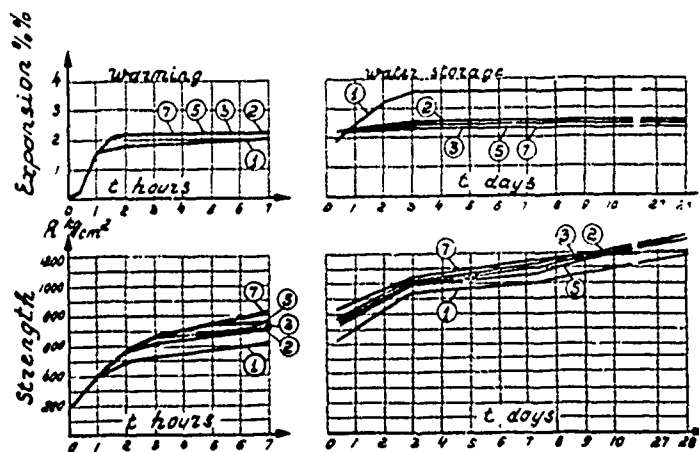


FIGURE 11. Expansion-strength diagram of stressing cement paste for various durations of water heating, at 80 °C.
Data in circles show number of hours of heating.

perature. Therefore, the structure destruction period is moved backward, and the period when new connections arise in the process of dissolution and hydration of silicate materials in the cement is moved forward. As a result the following sequence was set for hydrothermic treatment of SC mortar: 6 hr heating in water at 100 °C (boiling water), with initial strength about 160-200 kg/cm². Here mortar expanded very little, with specimen strength increasing to 300-400 kg/cm². During further water hardening, expansion progressed rather evenly, stopping after 3-10 days of water storage.

During expansion, mortar strength either did not change or slightly increased.

In this case the expansion mechanism generally acts, only the process takes several days, giving the hardening of C₃S and C₂S time to heal the recrystallization ruptures which have appeared.

Further experimental work [56] showed that this self-stressing mechanism is the best available, and it was somewhat improved to make the allowed expansion time less than 3 days. Additional investigations were then undertaken. Equipment was built for self-stressing mechanism investigation (fig. 12), which could reproduce elastic resistance of any amount. Each chosen degree of rigid

resistance corresponded with a certain coefficient of linear system reinforcement, i.e., reproduced any required percentage of concrete reinforcement.

Prisms of sizes 100 × 31.5 × 31.5 mm and 300 × 50 × 50 mm, with strips embedded at the faces, were selected as experimental specimens. Cylinders with transverse spiral wire coils were also investigated, whereby limited elastic volume expansion was obtained.

The investigations of self-stressing showed that elastic resistance increase against specimen expansion leading to self-stressing variation may be expressed approximately by the following equation:

$$\sigma_c = \sigma'_c \sqrt[6]{\frac{\mu}{0.24}}$$

where σ_c = unknown reinforced concrete self-stressing, in kg/cm² with reinforcement μ , σ'_c = reinforced concrete self-stressing with $\mu' = 0.24$ percent, μ = concrete reinforcement coefficient.

By investigation, a very important and vital feature of SC structure was found, relating both to theory and practice. For very large free stressing-cement expansion, uniaxial elastic resistance of sufficient intensity decreases expansion

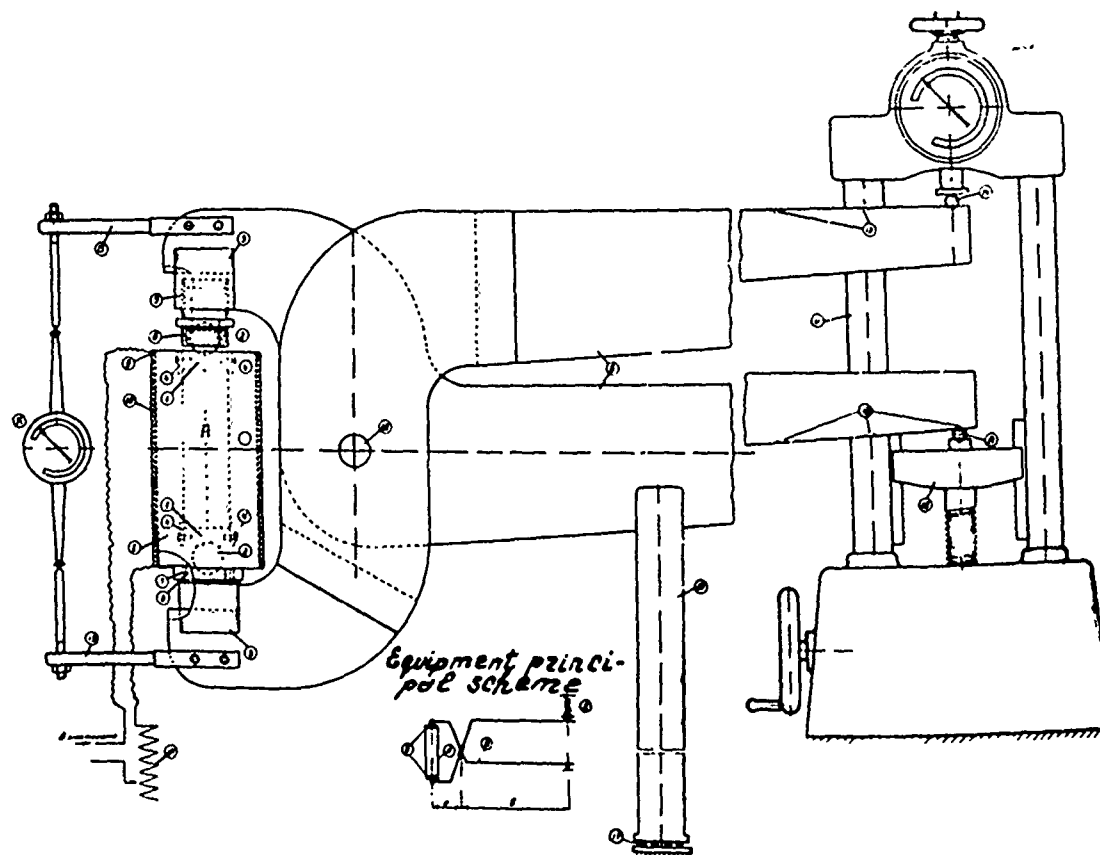


FIGURE 12. Measuring instrument for testing cement paste expansion force.

by 10 times not only in the direction of action of the resistance but crosswise as well.

This is explained by the strength and volume stability of the system resisting transverse plastic deformations, under uniaxial compression, if cement composition and the hydrothermic sequence of treatment are optimal and there is no drop in concrete strength during self-stressing.

Equipment for investigation of self-stressing power is made to imitate every hydrothermic sequence and all conditions of variable moistening and drying of specimens.

Self-stressing investigations [55] have shown that every portland cement may be employed for production of SC by adding high-alumina cement and gypsum. The only problem is to find the optimal proportioning.

1. If high-aluminate portland cement has rich C_3A content, SC from this cement possesses high expansion, but does not stabilize rapidly.

2. If brownillerite portland cement is used, without C_3A expansion, SC from this cement stabilizes rapidly, but with less expansion value.

Good results in our experiments were obtained with alite portland cement having the following average mineralogical content:

C_3S	C_2S	C_1A	C_4AF	CaO	MgO	KH
47.02	24.44	12.53	10.46	0.50	4.06	0.004

Using this cement, the SC content proportions selected were 14:20:66, which were checked in comparison with the higher activity SC proportions 18:22:60.

Figure 13 shows the curve of SC strength increase at normal temperature, 22 °C, for storage in isolated conditions under a paraffin layer.

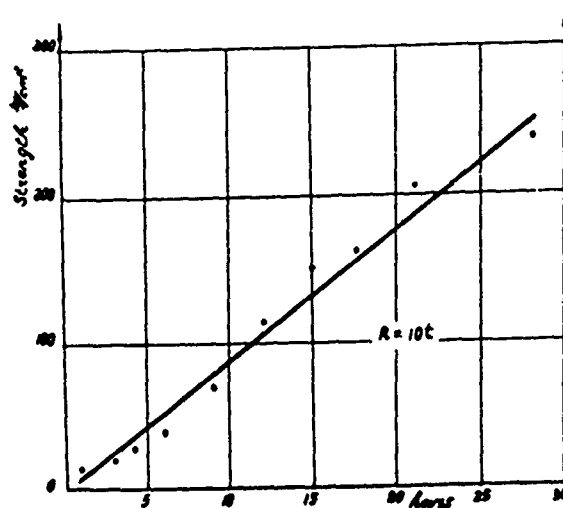


FIGURE 13. Strength increase of SC mortar isolated in paraffin.

Essentially the linear law of strength increase is maintained, being expressed by the equation: $R=10t$; the strength required to be attained during isolated hardening, about 200 kg/cm², is reached after 24 hr.

The selected SC components passed systematic and prolonged checking in pastes and 1:1 mortars, to establish the time stability of their mechanical properties.

Investigations were carried out on expansion, water absorption, strength in "free" and restrained conditions, self-stressing value in relation to degree of reinforcement (average for possible use, 1 percent), and other properties.

For selecting the required quantity of high-alumina cement with 14 percent gypsum, many combinations were investigated, by varying high-alumina cement content from 4 to 32 percent.

Results of 28-day investigation of SC mortar are shown in figure 14. Optimal high-alumina cement admixture of 18-20 percent gives the highest strength, 650 kg/cm²; highest expansion, 2.1 percent; and maximum water absorption, 6 percent (by weight).

Investigation of SC mortar properties with respect to time is shown in figure 15. Here during 6-hr heating: strength of "free" specimens increased from 160 kg/cm² to 268 kg/cm², and strength of restrained specimens increased to 310 kg/cm²; expansion and water absorption were low, 0.20 percent and 0.5 percent, respectively; self-stressing equalled 16 kg/cm². In further water storage, at 28 days the strength was 420 kg/cm² for "free" specimens and 450 kg/cm² for

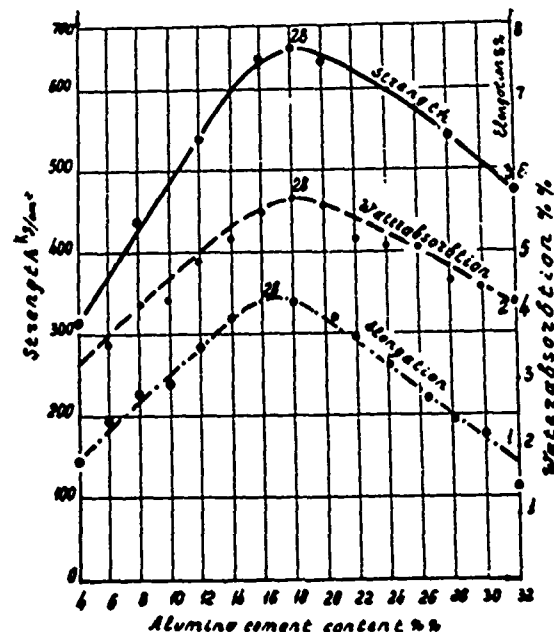


FIGURE 14. Elongation, strength, and water absorption of SC mortar (1:1) with 14 percent gypsum, versus alumina cement content.

Heated at 100 °C for 6 hr.

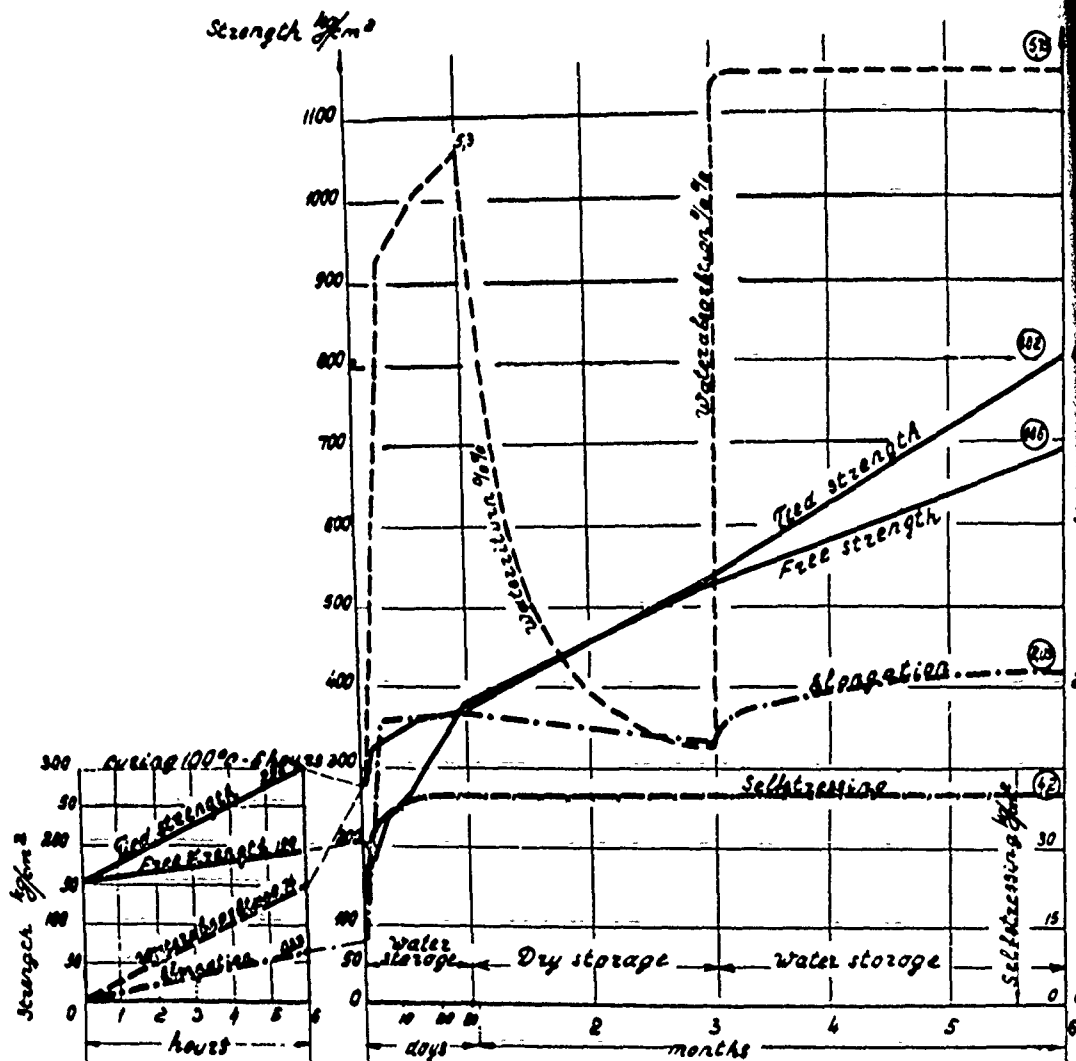


FIGURE 15a. Elongation, strength, and water absorption of self-stressing SC mortar (1:1), versus storage condition (water-

Proportions 14:20:66.

Heated at 100 °C for 6 hr.

restrained specimens; expansion was stabilized at 3 days (at 2.3 percent) with slight increase to 7 days; water absorption practically ended on the 14th day at 5.6 percent, and on the 28th day was 5.8 percent; self-stressing ended completely within 14 days and was 42 kg/cm².

After 6 months, the following results were obtained: strength of "free" specimens, 614 kg/cm²; restrained specimens, 740 kg/cm²; expansion, no change, i.e., 2.33 percent; water absorption, 6.7 percent; self-stressing, no change, i.e., 42 kg/cm².

It is important that during water storage the strength always continuously increases and reaches a high value, approaching 1,000 kg/cm² in 2-3 yr. We were more interested in the strength of restrained SC samples, as this is the chief characteristic limiting the relatively small deformations of reinforced self-stressed mortar.

At present, data are available on stable strength and the degree of self-stressing of SC mortar samples stored in water for 6 yr, this showing conclusively that all expansion processes are over, after the first several days of mortar existence.

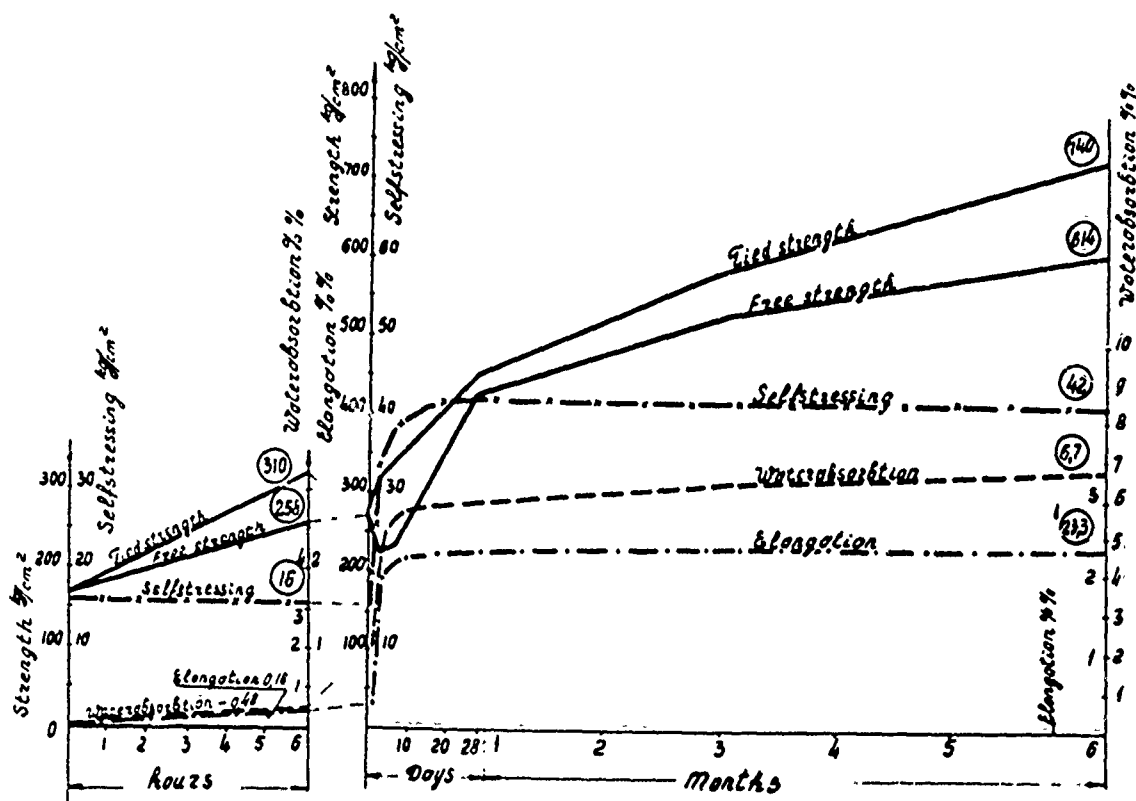


FIGURE 15b. Elongation, strength, and water absorption of self-stressing SC mortar (1:1).

Proportions 14:20:66.

Heated at 100 °C for 6 hr.

Water absorption of SC mortars is of some interest. Water absorption is sufficiently high—for some combinations, 7–8 percent. Naturally, not all water is used for $C_3A(CS)_3H_{32}$, C_4AH_{13} , and other formations. Apparently up to 70 percent of this water should be considered as hygroscopic moisture. However, it is very characteristic that, during drying, this water leaves the system slowly, but is absorbed again very quickly. Apparently, the capillaries in the structure are widely branched and very fine, this explaining the complete impermeability of SC mortar. SC mortar samples 25 mm thick resist hydrostatic pressure of about 20–25 atm without any signs of sweating.

Absorption and water loss properties are clearly shown in figure 15 for SC mortar (1:1); cement composition 14:20:66 with hydrothermic treatment at 100 °C for 6 hr. Strength of restrained specimens is 802 kg/cm² after 6 months.

Mortar specimens absorb 5.3 percent water in 28 days. Removed from water and exposed to

natural drying conditions for 2 months they lost 3.5 percent of the absorbed water and retained only 1.8 percent. Again immersed they reabsorbed the lost amount of water. It should be noted besides that a large variation of the moisture content of SC mortar slightly changes specimen length. Thus, 1.8 percent expansion at 28 days is lowered, as a result of 2 months isolated storage, to 1.6 percent, i.e., by 0.2 percent. Further moist storage not only restores initial expansion, but exceeds it.

For combinations of optimum high-alumina cement content, water absorption is higher, some water remaining in the system no matter how long the specimens are stored in air.

Figure 16 shows data on water absorption and water loss of the 1:1 mortar for SC with 11 percent gypsum, and variable high-alumina cement content, 4–32 percent. Combinations containing 16, 18, 20, and 22 percent of the high-alumina cement absorb about 6.1 percent water and lose

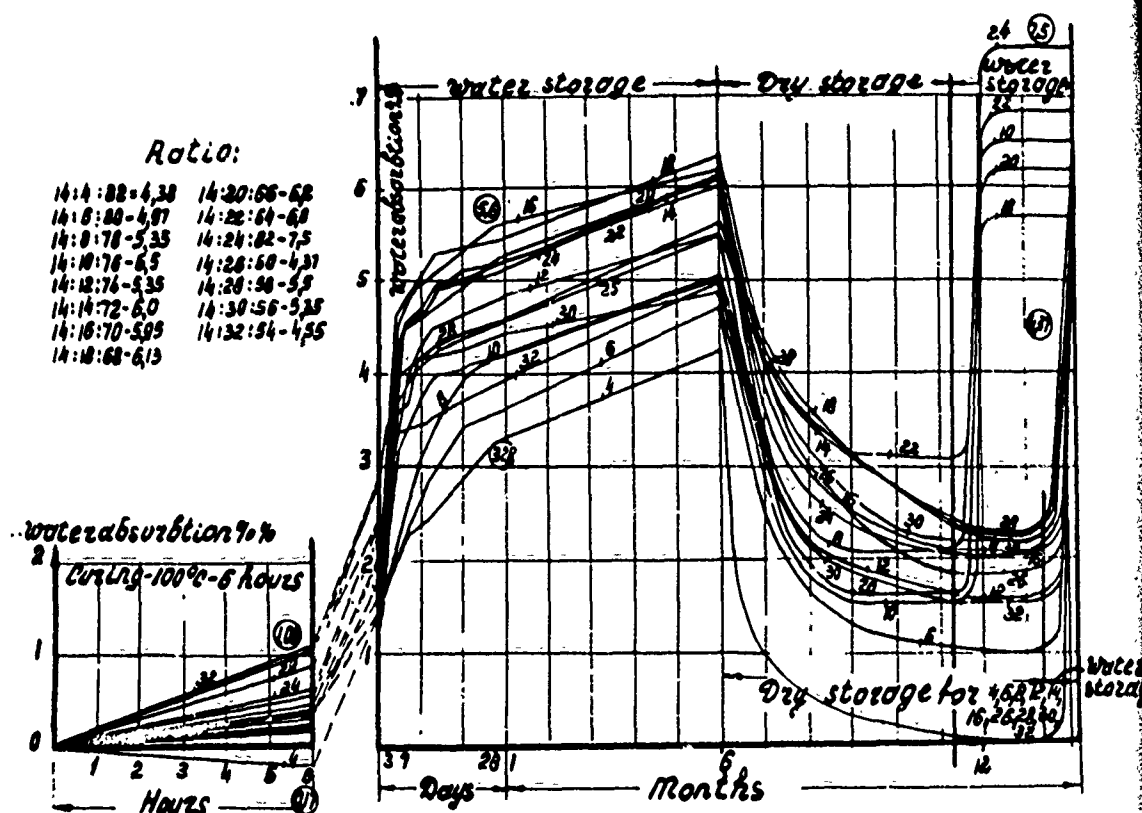


FIGURE 16. Water absorption and water loss depending on storage condition (water-air-water).

on the average 3.5 percent, retaining 2.6 percent. Combinations with 4 percent, i.e., almost without any high-alumina cement, absorb 4.2 percent and lose the same amount. As noted above, water loss during 6 and even 8 months is slow, while absorption is rapid.

Of some importance is the influence of the degree of repeated drying and absorption on self-stressing value. Does self-stressing disappear completely after some time? For determining this, expansive power measurements (fig. 17) have been made on 5 series of specimens differing only in hydrothermal treatment period: 1, 2, 3, 4, and 6 hr (see graphs from top to bottom). The sequence for all samples: water—20 days; air—15 days; water—20 days; air—20 days; water—25 days; air—35 days.

The investigations have shown that during drying about half of the initial self-stressing value is lost. Repeated moistening restores almost the entire self-stressing value. During these investigations it was determined that samples heated 6 hr lose practically nothing, i.e., during moistening they completely restore the initial self-stressing. The samples heated 2 hr irrevocably lose up to 15 percent of the initial self-stressing after several drying and moistening cycles.

Consequently, 6-hr hydrothermic treatment has several advantages over 2-hr treatment and it

should be recommended for production of self-stressed structures.

Figure 18 shows investigations of strength and expansion of 1:1 mortar made with SC proportioned 14:12:74. In one case it received normal hydrothermic treatment at 100 °C for 6 hr and then water storage, in another case it underwent natural hardening in the paraffin-isolated condition. The specimens hardened in paraffin isolation for 14 months.

The mortar (1:1) that received normal hydrothermic treatment reached after 14 months of water storage a strength of 900 kg/cm², and expanded 1.9 percent at 10 days. Isolated dry stored mortar had a very low strength—155 kg/cm²; apparently, the calcium hydrates and hydrosulfoaluminates during formation and partial recrystallization absorbed the entire mixing water reserve (30 percent); there was not enough water for C₃S and C₂S hardening, and hydration stopped. In this case, specimen expansion was 3 percent, thus higher than for the first group. When, after 14 months, samples were immersed, water absorption was so rapid and the forces caused by calcium hydrosulfoaluminate recrystallization so large that the samples were rapidly and completely demolished.

The behavior of SC mortar specimens that had received hydrothermic treatment shows that SC

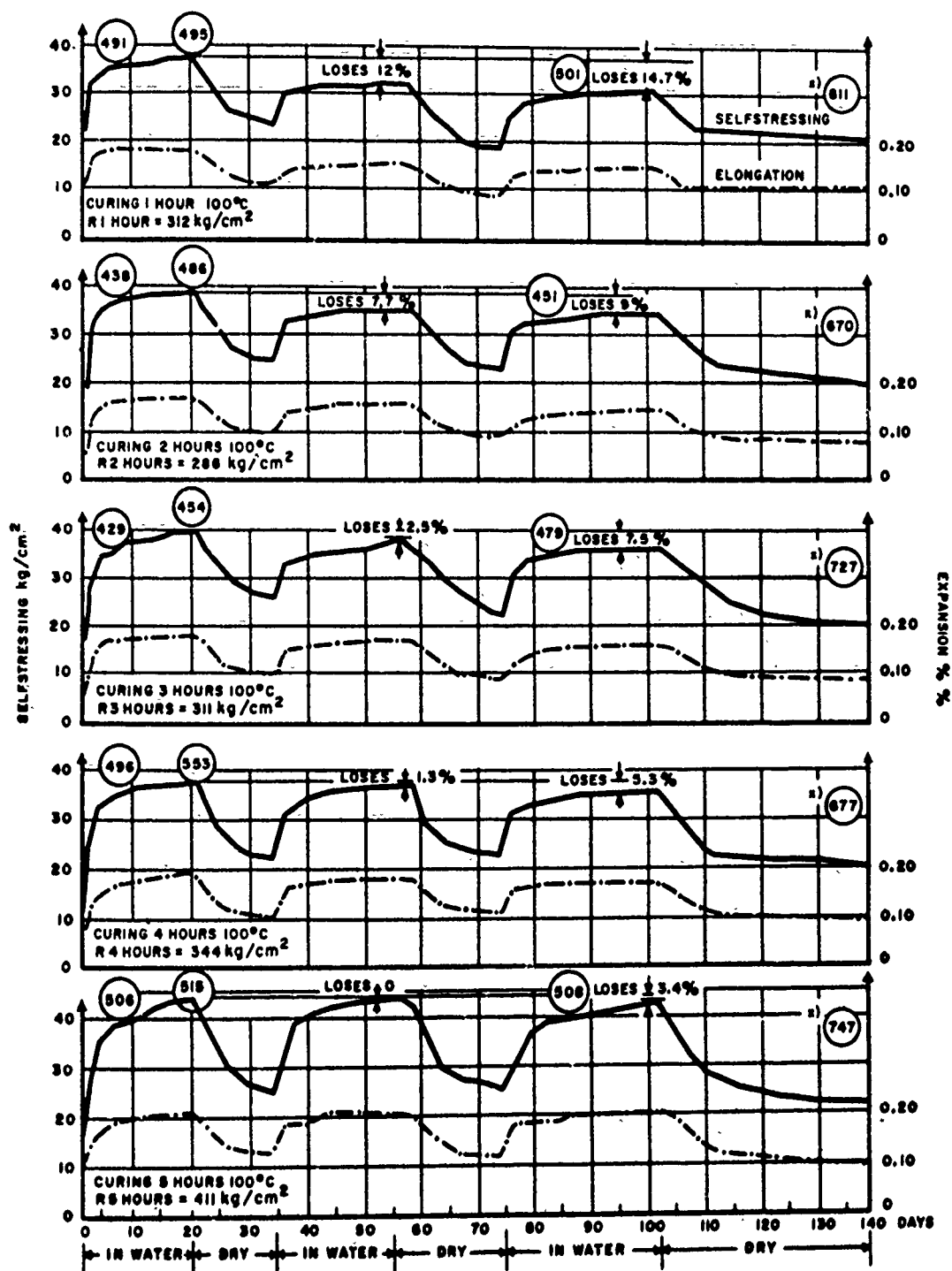


FIGURE 17. Wetting and drying condition of self-stressing SC mortar (1:1).

Proportions 14:20:66.

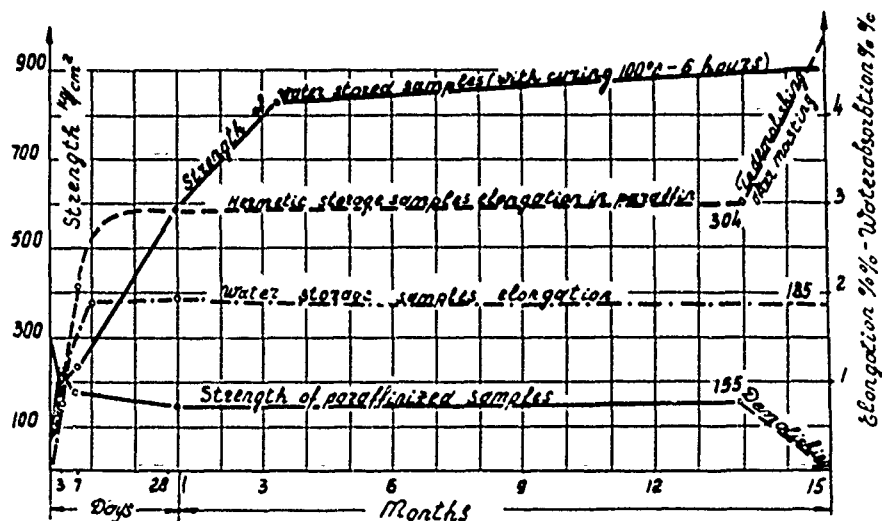


FIGURE 18. Influence of water storage on elongation and strength of SC mortar (1:1) after heating at 100 °C for 6 hr in comparison with paraffin-isolated SC mortar (1:1) hydrated without heating.

Proportions 14:12:74.

is a full-value hydraulic cement because of its hydrothermic treatment and its maximum strength reached during long-term moist storage. Therefore it should be employed for structures under pressure, in pressure pipes, tanks, in underground structures, and in highly moist conditions.

During investigations of SC mortars (1:1) it was found that the lower the water-cement ratio, the higher the self-stressing and strength. Very short SC mortar setting period, 2 min, hampered mortar batching and placing in molds. Vibratory mixing and vibratory casting, and cement retarding agents like lignosulfonates, were therefore necessary ($\frac{1}{2}$ percent sulfate-alcohol waste additive or tartaric acid, $\frac{1}{10}$ percent technical). These setting-retarding methods are effective, but in both cases the degree of expansion is lowered and self-stressing is about 30 percent less. This is caused by the fact that in both cases there is destruction of the initial, rather friable, but very convenient frame structure of self-stressed SC, owing to which the frame structure, an essential part in expansion, is without strength in the spaces free of cement glue.

The self-stressing of 1:1 stressing mortar makes it possible to obtain an average concrete self-compression value in the range 20 to 50 kg/cm². This self-compression is the result of the structural reinforcement's elastic resistance to expansion, there being stressing to different degree, depending on reinforcement dimensions, over the range of 14,000 kg/cm² to 3,000 kg/cm², for 0.15 to 1.5 percent of reinforcement. For many structures such a prestressing value gives a satisfactory effect. With reinforcement higher than 1.5 percent, the concrete self-stressing intensity remains almost unchanged. However, the self-stressing value in the member sections may be changed as a result of a technological action, which we call "stress

calibration". By special methods of stress application, both before and after hydrothermic treatment, it is possible to redistribute reaction forces in a member to any limit, and then the degree of fiber stresses in concrete may reach at least 150 kg/cm².

It should be noted that investigations have been made in the USSR in the coal mining industry when designing structures for reinforced concrete mine propping. The main requirements for propping members are low weight and high load capacity (about 10 tons/m²). During investigation of self-stressed vibrated bracings (channel type) with 0.75 percent reinforcing of the bracing section and 1.8 percent in the bracing tensile zone reinforced with high strength wires, the following stressed bracing conditions were obtained, by hydrothermic treatment for 6 hr at 100 °C and then 3 days water storage. High (6,000 kg/cm²) stresses in the upper reinforcement and comparatively low (1,500 kg/cm²) stresses in the lower reinforcement resulted in uniform compression of the concrete bracing, intensity 22 kg/cm².

The "stress calibration", [55] employed for bracings at stresses of 8,200 kg/cm² of the lower reinforcement made it possible to redistribute the stresses. Then the lower reinforcement in the middle part of bracings received a stress of 6,900 kg/cm² and the upper a stress of 800 kg/cm². The diagram of concrete stress distribution of the bracing section now shows the following fiber stresses: at bottom 200 kg/cm² and at top -47 kg/cm² (tensile). The method of "stress calibration" is still new and practical application will be possible, after much testing.

All above-mentioned SC mortar investigations refer to vibration during mixing and placing, owing to which the average self-stressing value obtained—40 kg/cm²—is lower than the actual

SC mortar self-stressing value, about 60 kg/cm², not yet reached for vibrated samples. The actual self-stressing values, corresponding to the SC chemical possibilities, were obtained with SC mortar by shotcreting. The dry mixture, delivered from the cement gun by compressed air at a pressure of 3-5 atm through a hose to the nozzle, was moistened at that point by water under pressure, and then thrown with high speed against the surface of the cast article. From the

6. Mikhailov²¹ described the use of self-stressing concrete produced by expansive cement in the manufacture of pressure pipe as follows:

In the USSR the technology and equipment are simultaneously being worked out for three methods of manufacturing self-stressed pipes: shotcreting, centrifuging, and vibrosqueezing. Each of these methods provides for manufacture of pipe of specific diameters: shotcreting for pipes of dia. 600 to 1,000 mm, centrifuging for pipes of dia. 300 to 500 mm, vibrating-squeezing for pipes of dia. 150 to 250 mm.

The pipes manufactured by these technological methods retain internal pressure, without sweating, up to 15-20 atm, and may be used for operations under working pressures of 6 and 10 atm.

A special two-seat automatic machine (fig. 19) has been designed for making pipe by shotcreting. The automatic machine is equipped with a slowly rotating core (4), with foldable mechanism to make clearance between the shotcreted pipe and core. Besides, the machine has a rotating coil and wire reel (8), which may either be held by an electromagnet (7) and moved up and down with a platform (3), winding wire around the pipe, or may turn together with the core, remaining in the bottom no-work position (as shown in fig. 19). A set of nozzles is installed through which the SC mortar is shotcreted on the core to form the pipe. While the pipe is being manufactured in one station (LH), the other (RH) is used for preparatory operations. During rotation of core and motion of the platform (3) up and down, shotcreted layers are placed at the same time as the reinforcement coils. When the last layer is being placed, the surface is smoothed with a mechanical knife. After the first pipe casting (in the LH station), the set of nozzles is turned 180° and shotcreted the next pipe (in the other station), and so on. In the first station, the core is retracted and the pipe is removed by lifting it onto a round support and is transferred for further technological treatment, while the core is prepared for new shotcreting.

Figure 20 shows the technology worked out for self-stressed pipe manufacture. The shotcreted pipe, already hardened due to the quick setting of SC, is lowered for 1 min into a pit filled with melted paraffin to make a thin isolation layer, and is then stored for 18-24 hr at normal temperature, which gives the pipe a concrete strength of 200 kg/cm². Then the pipe is placed for 6 hr in boiling

moment of moistening to placement by the gun, only hundredths of a second passed. Therefore, mortar placed by shotcreting is very dense, with minimum water content (about 0.20-0.22) and it is placed long before SC setting begins.

The advantages obtained by shotcreting technology can be enumerated: self-stressing reaches 50-60 kg/cm², and the strength at mature age is 80-1,000 kg/cm².

water, and into a cold water tank for 5-6 days storage. Finished pipe receives face leveling and hydraulic testing, and is transferred to the warehouse, where it is kept for 21-28 days.

The centrifugal technology of self-stressed pressure pipes has been checked at a Moscow pipe factory. Self-stressed pipes of 400-mm diameter, 50-mm walls, and 4 m long are manufactured there, whereas open channel pipes were previously made in solid molds using paraffin. Difficulties of the short setting time of SC were eliminated by use of a mixer equipped with a vibrating device. Ten min vibromixing destroyed the initial structure to a degree, so that the mixture retained plastic consistency for 30 min, sufficient for centrifuge casting. Pipe manufactured in this way with reinforced frame of stressing mortar was held in paraffin coating 24 hr during which the concrete strength reached 160 kg/cm². The pipe was next heated in a bath 6 hr at 100 °C, and then delivered for water storage. Internal pressure testing of these pipes showed that pipes with weak reinforcement resist internal pressure to 11-12 atm. Wound with prestressed design spiral reinforcement the pipe resists 25-28 atm pressure without leakage. Pipes without stressed coils can be used for pressure piping under 6 atm pressure, with winding for piping water at heads of 10 atm and above.

The technology of pressure pipe vibrocasting of small diameter pipe—150-200 mm, 2 m long, and with 25-30-mm walls—has been mastered on a vertical vibrosqueezed pipe casting machine, now industrially used (fig. 21). These pipes are equipped with spigots and are for use in water distribution lines and in pipings for water supply in rural areas with a working head of 4-6 atm. The pipes have cold-drawn wire reinforcement, diameter 4-5 mm.

The vibrosqueezing method of manufacture consists of a vertical vibrating mold slowly filled from the top with SC mortar mixture. A simultaneously vibrating core, introduced from the mold bottom, moves up and down rotating from one side to the other repeatedly, and distributes and tamps the mortar into pipe body and spigot. The simultaneous vibration of core and mold aids in compacting stiff mortar and in casting pipe. When the vibrating core is removed from the mold

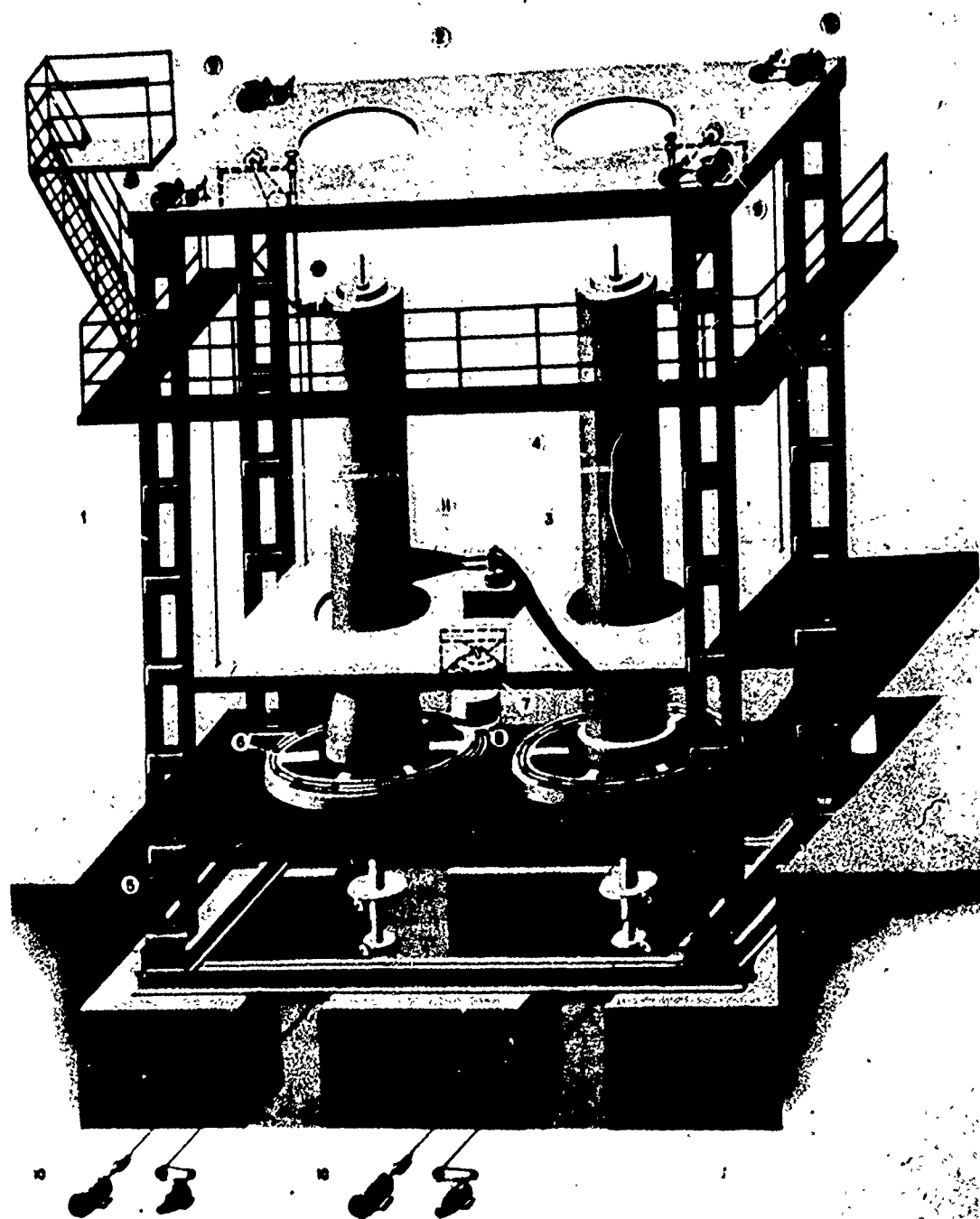


FIGURE 19. Scheme of industrial automatic shotcreting machine for large-diameter, high-pressure pipe products

1. Stand
2. Upper platform
3. Movable platform
4. Collapsible metal core
5. Lower platform
6. Revolving table
7. Magnetic chuck (or clutch)
8. Spool with wire
9. Elevating motor
10. Motor for rotating table
11. Nozzles
12. End-forming device

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FIGURE 20. *Technology sequence of high-pressure pipe production by shotcreting.*

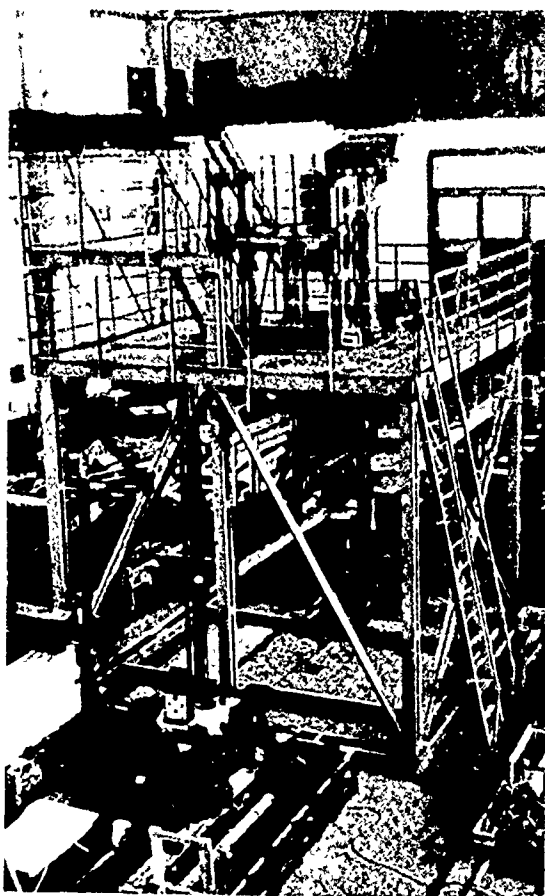


FIGURE 21. Research vibrosqueezing machine for small-diameter, high-pressure pipe production.

at the top end it pushes out excess mortar (if there is any) from the pipe. At this time vibration is switched off, and the core, while turning toward one and the other side, is pushed down, sliding along the internal pipe surface and smoothing it. The machine simultaneously casts two pipes over two cores. After the pipe casting process is finished, the molds are removed from the machine and are stored 12-18 hr, during which the concrete reaches a strength of 200 kg/cm². Then delivered pipes are heated 6 hr in a bath at 100 °C, when the pipe mortar reaches a strength of about 300 kg/cm². During subsequent water storage for 3-5 days, the mortar expands and pipe concrete and reinforcement are self-stressed. Here, as well as when centrifuging, vibrated mixing of the mortar occurs before and during the filling of the molds, due to which a significant part of the self-stressing is lost.

Testing of such pipes by internal pressure has shown that they have high impermeability. Even though 20-25 mm thickness of the wall is small, the pipes resist an internal pressure of 17 and even 25 atm without sweating.

A similar sequence is employed for manufacturing and testing pressure pipes by shotcrete casting. A horizontal spraying machine is used for shotcrete casting (fig. 22). In 1958 this machine was redesigned and is now equipped with mechanism for winding spiral reinforcement at the same time as shotcreting. It must be pointed out that previously whenever frame reinforcement was put on the shotcreting process had to be stopped, and it was necessary to remove the pipe with the core from the machine, to tighten the next reinforcement frame, and then to reinstall the pipe on the machine for further shotcreting. If the pipe had more than two reinforcement frames, shotcreting had to be stopped twice. This complicated the casting process and worsened the

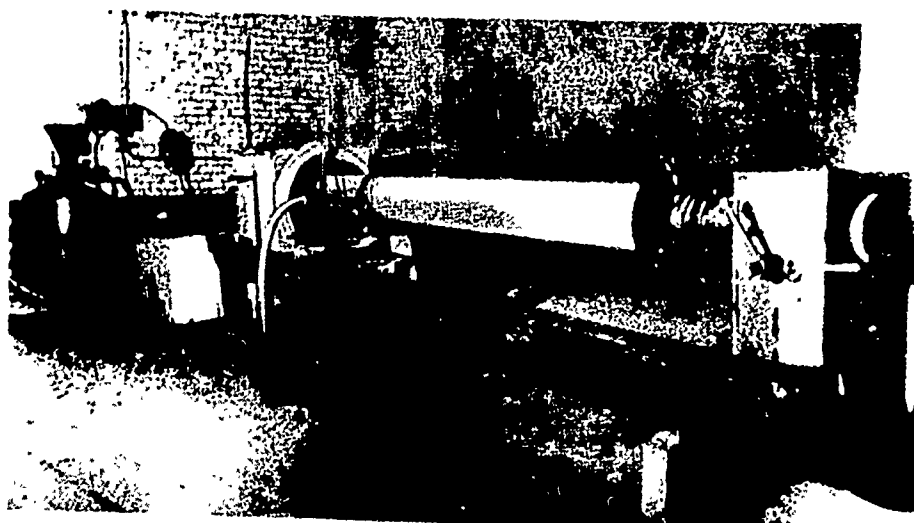


FIGURE 22. Experimental shotcrete machine for casting high-pressure pipe simultaneously with wire winding.

density of mortar under the spiral frame. Simultaneous winding of spiral reinforcement during the shotcreting process results in marked lowering in casting time, permits winding many rows with a wide pitch, reliably coats mortar around spiral wire, and may eliminate the need for longitudinal reinforcement.

As a result of shotcrete casting, with simultaneous entire pipe-body winding (throughout the entire wall depth) the spiral reinforcement with interwinding coils of adjacent rows is distributed uniformly in the concrete. In this condition mortar deformations during expansion are slight, thus insuring better use of mortar expansive power and corresponding maximum pipe self-stressing. During the mastery of new type shotcrete casting, it was found that simultaneous winding is the

best method of reinforcing self-stressed pipes. Shotcreting needs a nonretarding admixture. Under these conditions the structure formed cannot later be destroyed. Due to the very low water-cement ratio, 0.16-0.22, the maximum quantity of "low-sulfate" hydrosulfoaluminate of calcium is formed and, consequently, maximum power is released for expansion and self-stressing during recrystallization into the "high-sulfate" form. This has been entirely verified by tests. In all cases shotcrete mortar specimens had high expansive force, and produced mortar self-stress of about 40-50 kg/cm². These results permit us to consider shotcrete casting as the chief method for manufacture of large diameter pressure pipes. Self-stressed shotcrete concrete has high stability in aggressive media, sea water in particular.

7. Mikhailov²¹ concluded his review as follows:

The idea of self-stressed structures, . . . is new in the field of prestressed reinforced concrete. The present level of development of the self-stressing method is progressive in character and has wide perspective for construction use, but also indicates need for further study to improve cement composition and retarding admixture for setting, and need for investigation of more effective self-stressing methods, including water hydration without heating and the method of "stress calibration," in order that one may progress from mortars to concrete with less binding material.

In the USSR, besides the explanation of self-stressing already discussed, G. N. Sivertzev holds another opinion, completely denying the possibility of calcium hydrosulfoaluminate formation in cement media and giving a different explanation for causes of expansion and self-stressing. Sivertzev considers that expansion may develop independently of formation or lack of calcium hydrosulfoaluminate, and that the contradictory phenomena occasionally observed during SC hardening are explained only by colloidal chemistry. Expansion is considered by him to be determined by the unstable dynamic equilibrium of two mutually contradictory processes, namely SC setting and hardening, and solvation processes of SC particles retarding coagulation. SC is marked by the presence of certain antagonistic suspensions (portland cement, high-alumina cement, gypsum, etc.). Here each type of solvate shell of the particles is formed separately, without disorientation of water dipoles, preventing adhering of particles. As the solvate shells cause cement paste expansion, the structure densifies and strength increases. Solvation and expansion develop with unavoidable structure friability and strength drop. During the hydration of ordinary nonexpansive cements, in dense pastes, the solvate shells invariably interfere, causing disorientation of the water dipoles and solvate shells. The solvate shells in this case

lose their stable function and aid the direct cohesion of hardened cement paste particles. Sivertzev is conducting very interesting investigations to corroborate and broaden his views on SC expansion and self-stressing processes.

In France much work in the field of expansive cement has been done by the French scientist H. Lossier,^[57] who has produced his own expansive cement. This cement is composed of portland cement, sulfoaluminate cement, and slag, dry-ground in the proper proportions. Fifteen-day hardening in moist condition causes complete expansion and densifies the structure. According to Lossier, resistance should give self-stressing.

The theoretical conclusions of Lossier clearly show the established order and views on cement, and also show that scientists experimenting in this field must find the best mineralogical cement composition, the necessary additives, and the appropriate water content. The view is that the structural synthesis during cement setting and hardening takes place by itself, and forms the cement paste of required characteristics. This is beyond human influence. At best, the required structural formation processes may be accelerated by normal heating or high pressure. This considerably handicaps the designer, when it comes to the mixed cement passing through the required stages (fig. 7) of structural formation and strengthening.

P. S. Rehbinder and N. V. Mikhailov proposed intervention in the processes during the first stage. When preparing very fine cement, ground sand, and active mixture they recommend the use of mechanical influence like vibratory mixing of concrete and multifrequency vibration in all technological stages of mixture processing. This destroys the formed structure, to obtain denser packing of concrete and cement paste particles and development of hydration processes deeper in the cement grains. As a result there is a significant increase of concrete strength and density.

Our aims are broader: we prepare a binder so that the stage of structure formation passes quickly and setting is also rapid. We assume that the cement structure has entered far into the setting stage to form a sufficiently strong and hard cement paste body. With any absorption of water into this structure, even though it is very strong, expansion of cement paste completely destroys the structure, turning it into a jellified substance. Thus, the created structure conceals possibilities of self-demolition. In this respect SC is completely useless as a binding agent. But here the researcher intervenes in cement paste structure building and by definite processes (moistening, heating, mechanical force) rearranges the system, destroying certain cement paste structures, while others arise rapidly in the combinations and sequence required for the hard body to remain unchanged, so that strength is maintained and even increased, while the cement paste volume increases, able in case of resistance

8. Brown⁵⁸ noted, in discussion of Mikhailov,²¹ that:

The advent and rapid development of prestressed concrete design and construction has opened a new field of broad application. Among the more intriguing variations is that of an expanding concrete member, essentially an expanding cement, whereby the desired prestress is self-effected. It is evident in the wealth of data presented in this paper that the concept, both of the cement and of its effective use, has developed into an established art. While the accomplishment merits high compliment, there are two or three facets of the report that may merit more extended discussion.

The unstable or expanding component of the cement (or concrete) is identified as low sulfoaluminate, proportioned about 35 to 65 percent portland cement. It is put into the cement as the two substances calcium aluminate and gypsum, properly proportioned. It is preserved in the low form by limited quantity of mix water. After thorough set, the hardened member is immersed in water. The availability of the extra water promotes alteration of the low sulfoaluminate to the high sulfoaluminate. The expansion is accomplished by this inversion. The expansion tends to disintegrate the formerly hardened member, which action of course is minimized by restricting the potential expansion, i.e., the low sulfoaluminate, to smaller proportions. If the expansion-curing is augmented and accelerated by heat, it is found that strength is maintained by autogenous healing. Thus a member may expand 3 percent or more, and the concrete still show a strength equal to or greater than that of the initial material. Test data, offered in some abundance, show this to be the eventual effect.

In practical application, a fixed principle of such expansion is that it is triaxial and that interior voids or discontinuities tend to increase in diameter. That is, the envelope of concrete about a prestressing wire tends to enlarge and thereby weaken bond and the desired composite action. Incidentally, elongation of the prestressing wire

to convert deformation power into the work of reinforced concrete stressing.

Thus, cement acquires new qualities, previously not only not used, but even objectionable and in every way undesirable.

The possibility to direct the expansion of hardening binders, and freely to design them, is a new advanced undertaking in cement chemistry, opening wide technical horizons.

The work performed by Soviet scientists in this field is a first step towards using the chemical power of hardening binders, and must be continued in order to find the best way to release and make use of chemical forces inherent in the binders for advantageous work in self-stressing. The efforts of scientists and engineers of many countries should be directed towards this end. It seems to us that maximum results are assured if producers will participate in this work and introduce new achievements in their experimental plants.

reduces its diameter and tends further to weaken the bond. This tendency is inherent in the process and should ever be kept in mind. That is to say, the adverse tendency does not necessarily vitiate the objective. It only means that one should be aware of corrective countermeasures. It may be that the autogenous healing automatically restores the bond. Then again, it is noted in the paper that uniaxial restraint tends to transverse compression, an explanation that is subject to serious challenge.

Many properties of the eventual concretes are investigated and described. Among others, a high resistance to sea water or sulfate exposure is noted. That probably is to be expected, since the aluminate is already in the stable high sulfate form. The concept offers intriguing possibilities in respect to endurance of ordinary concrete.

Nothing is said of one property that could be of wide interest. That is resistance to frost action. It is noted that before expansion the concrete is very dense and that it dries out very slowly. When put in water, however, it takes up water very rapidly. This anomalous behavior is quite different from that of conventional concrete. One may well suspect thereby that resistance to frost action could be poor, but no freezing and thawing tests were noted.

Much of the first part of the paper is made a dissertation on the processes of hydration and set of ordinary cement. While it is evident that intensive petrographic studies have been made, the concepts derived do not appear in full accord with conventional thought. For example, it is stated that the original cement particles shatter into much smaller colloids. Our petrographic studies do not support this view. Present purpose however is not to criticize the concept. It is only to note that the dissertation is not essential to discussion of the mechanism of expansion and self-stressing. The discussion suffers somewhat from this earlier and lengthy consideration.

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